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Lane, B. H., 1935, Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C. 40c.)

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LEAD-ALPHA AGES OF SOME NEW HAMPSHIRE GRANITES*

J. B. LYONS, H. W. JAFFE, D. GOTTFRIED, and C. L. WARING

ABSTRACT. Age determinations by the Larsen method are reported for four plutonic series of Paleozoic age from New Hampshire, a plutonic series of uncertain age from southeastern New Hampshire, and for granites of Middle Devonian age from Maine and New Brunswick. Mean values for the measured ages are: Highlandcroft (Late Ordovician) 385 ± 27 million years; Oliverian (Middle Devonian) 311 ± 26 million years; New Hampshire (Middle Devonian) 296 ± 29 million years; southeastern New Hampshire plutonics (Middle Devonian) 294 ± 12 million years; White Mountain (Permo-Triassic) 186 ± 14 million years; and Maine and New Brunswick granites (Middle Devonian) 315 ± 11 million years. For the most part, these ages agree with the geology and with other reported ages for rocks of the northern Appalachian region.

INTRODUCTION

The Larsen method (Larsen and others, 1952) for determining ages of plutonic rocks is based upon the measurement of alpha activity and total lead content of selected accessory minerals concentrated from fresh igneous rocks. This paper reports the results of the application of the Larsen method to the four plutonic series of Paleozoic age from New Hampshire (Billings 1937, p. 499-511), to some plutonics of uncertain age from southeastern New Hampshire, and to some granites of Middle Devonian age from Maine and New Brunswick. This study is an outgrowth of an investigation of the radioactivity of the four plutonic series currently being conducted by the U. S. Geological Survey on behalf of the Division of Research of the U. S. Atomic Energy Commission. It seemed appropriate to make these age determinations as a check on the general utility of the Larsen method, inasmuch as the plutonic rocks are fairly well dated geologically within the Paleozoic.

Several sources of systematic error are possible with the Larsen age method aside from those possibly introduced by unrecognized impurities in the samples.

The lead-alpha age of a mineral is calculated from the following equations:

$$(1)\ t = \frac{c\,Pb}{\alpha}$$ (Larsen and others, 1952, p. 1049),

where t is the apparent age in millions of years, c is a constant based upon the Th/U ratio and is equal to 2632 if uranium alone is the radioactive element and 2013 if thorium alone is the radioactive element, Pb is lead in parts per million, and α is alpha counts per milligram per hour.

$$(2)\ T = t\text{-}1/2\ kt^2$$ (Keevil, 1939),

where T is the age in millions of years corrected for parent decay of uranium and thorium, and k is a decay constant based upon the Th/U ratios and is

* Publication authorized by the Director, U. S. Geological Survey.

equal to 1.90 x 10^{-4} if uranium alone is the radioactive element and 0.49 x 10^{-4} if thorium alone is the radioactive element. Where t is less than 200 million years, the decay correction is negligible and equation (2) is not required for calculation of the age.

When uranium and thorium analyses are not available, Th/U ratios of 1, 25, and 0.5 are assumed for zircon, monazite, and xenotime, respectively, based upon a review of analytical data obtained on representative samples (Gottfried, 1957, verbal communication), and the following c and k constants apply:

Mineral	Th/U ratio (assumed)	c	k x 10^{-4}
Zircon	1	2485	1.56
Monazite	25	2085	0.65
Xenotime	0.5	2550	1.71

The choice of these values for c, made without benefit of uranium and thorium analyses, will yield a maximum possible error, in the age, of approximately 7 percent if the assumed Th/U ratios are seriously in error. There is very little difference between the mean ages for a given plutonic series calculated with and without uranium analyses. This fact is, in itself, a check of the essential accuracy of the constants based upon the assumed Th/U ratios.

Other errors may be introduced by incorrect measurements of the alpha activity or lead content. Duplicate measurements of alpha activity on the same sample are reproducible to within 5 percent of the measured value. Waring and Worthing (1953, p. 830-831) have demonstrated a high degree of reproducibility for spectrographic lead determinations where a series of tests are run on the same sample, but some single determinations may deviate by as much as 10 percent from the average.

Another assumption (Larsen and others, 1952), that there is no original lead in the minerals used for the age determinations, may also cause slight errors. Tilton and his co-workers (1955) have demonstrated that zircon from plutonic rocks has negligible amounts of original lead insofar as its effect on the lead-uranium or alpha-lead ages is concerned. A cyrtolite from Bedford, N. Y., however, is reported by Nier (1939), p. 158) to contain 6.2 percent of its lead as nonradiogenic lead. A small percentage of the lead in monazite may also be original lead (Jaffe, H. W., 1955, p. 1253; Report of the Committee on the Measurement of Geologic Time, 1948-49, p. 27), but this is in insufficient amounts to affect an alpha-lead age determination seriously. The assumption of no original lead in xenotime is made largely on the basis of crystal chemistry.

In this paper the maximum deviation from the mean age of a plutonic series is approximately 17 percent. Mean deviation for values reported here is less than 8 percent; standard deviation less than 10 percent. There is, thus, a reasonable probability that possible errors, as discussed above, partly cancel one another, and that the mean age of a plutonic series, as determined by the Larsen method, is close to its true age.

Mineralogic separations and alpha counts on the Highlandcroft, Oliverian, and New Hampshire plutonic series were made by J. B. Lyons and H. W. Jaffe; those on the White Mountain plutonic-volcanic series by D. Gottfried and H. W. Jaffe; those on the southeastern New Hampshire plutonics by Jaffe; and those on the Maine and New Brunswick granites by Jaffe, Lyons, and C. Ratte. Spectroscopic lead determinations were made by C. L. Waring, and most of the uranium analyses by Marian Schnepfe. The ages for the various geologic periods, in millions of years, are those published in the Report of the Committee on the Measurement of Geologic Time (1950, p. 18). These differ slightly, but not significantly, from those suggested by Holmes (1946).

In the following tables the thorium content of the minerals that have been chemically analyzed for uranium was calculated from the equation: $\alpha = 0.366$ U + 0.0869 Th, where α is alpha activity per milligram per hour, U the uranium content in parts per million, and Th the thorium content in parts per million (Senftle, F., verbal communication). In the tables where more than one age is listed for a given mineral the data represent separates from identical rocks differing either in magnetic susceptibility or crystal size.

HIGHLANDCROFT PLUTONIC SERIES

Rocks of the Highlandcroft plutonic series of late Ordovician (?) age have been mapped in four localities. West of Littleton, N. H., granodiorite of the Highlandcroft plutonic series intrudes the Upper Ordovician (?) Ammonoosuc volcanics and appears to be unconformably overlain by the Middle Silurian (Niagaran) Fitch formation (Billings, 1937, p. 500). The evidence, therefore, favors a Late Ordovician age for this series, although it cannot be more precisely dated than post-Late Ordovician (?) and pre-Middle Silurian.

Table 1 lists age determinations for the four known stocks of the Highlandcroft plutonic series. Their average age, 385 ± 27 million years, is in good agreement with the geologic age.

It is of considerable importance to note that all the rocks in table 1 were regionally metamorphosed to the greenschist facies during the Middle or Late Devonian. Despite this, the zircon was evidently not recrystallized, and its age dates the time of formation of the plutonic rock, rather than the time of its metamorphism. Whether zircon will recrystallize under metamorphic conditions of higher intensity is not yet known.

The best-dated northern Appalachian rocks that can be compared with the Highlandcroft plutonic series are pegmatites at Bedford, N. Y. and Branchville, Conn. According to Rodgers (1952, p. 419-420), the pegmatites are pre-Triassic, possibly related to the Thomaston granite of Late Ordovician (?) age, and lie east of the Precambrian core of the Hudson Highlands in schists of uncertain age. Chemical and mass spectrometric analyses of the Bedford zircon (cyrtolite) yield an age of approximately 340 to 350 million years (Rodgers, 1952, p. 420; Kulp and others, 1954, p. 354). Uraninites from the Branchville pegmatite range in age from 340 to 370 million years (gravimetric analyses), and have a mean Pb/U isotope age of 366 million years (Wasserburg et al, 1956, p. 154). The age of the Bedford cyrtolite is important be-

TABLE 1
Age Determinations on Zircon from the Highlandcroft Plutonic Series

Formation	Location	Mineral	α/mg/hr	Pb (ppm)	U (ppm)	Th calc. (ppm)	Th/U	c	k x 10^{-4}	Age (m.y.)
Granodiorite, Highlandcroft plutonic series	Littleton quadrangle	Zircon	166	26 (27,25)	342	475	1.4	2455	1.47	374
Fairlee quartz monzonite	Mt. Cube quadrangle	Zircon	164	25	n.d.[1]	n.d.	—	2485	1.56	368
Sodaclase tonalite	Hanover quadrangle	Zircon[2]	882	156	n.d.	n.d.	—	2485	1.56	425
Quartz diorite of Lost Nation group (of Chapman, 1948)[3]	Whitefield quadrangle	Zircon	200	31 (32,30)	n.d.	n.d.	—	2485	1.56	373
Mean age for series										385
Standard deviation										27
Ordovician										440-360 ± 10
Mean age, without uranium analysis										386 ± 27

[1] Not determined
[2] Partly metamict
[3] Age determination by H. W. Jaffe

TABLE 2
Age Determinations on Zircon from the Oliverian Plutonic Series

Formation	Location	Mineral	α/mg/hr	Pb (ppm)	U (ppm)	Th calc. (ppm)	Th/U	c	k x 10^{-4}	Age (m.y.)
Granite of Oliverian plutonic series	Mt. Washington quadrangle	Zircon	498	61	885	2002	2.3	2390	1.31	287
Border gneiss of Lebanon granite	Hanover quadrangle	Zircon	217	27	466	529	1.1	2475	1.55	301
Lebanon granite	Hanover quadrangle	Zircon	574	79	1385	771	0.56	2540	1.69	340
Aplite in Lebanon granite	Hanover quadrangle	Zircon[1]	980	130	2770	0	0	2632	1.90	337
Granite in Mascoma group (of Chapman, 1939)	Mascoma quadrangle	Zircon	514	61.5 (60,63)	1080	1372	1.3	2460	1.50	288
Mean age										311
Standard deviation										26
Devonian										320-265 ± 10
Mean age, without uranium analyses										311 ± 24

[1] Partly metamict

cause it is generally accepted (cf. Holmes, 1946; Rodgers, 1952) as marking the close of the Taconic orogeny and the end of the Ordovician period.

Some of the granites in southeastern Massachusetts, near Milford and Wrentham, have recently been shown by Webber and others (1956) to have a mean zircon-method age of 355 million years. These rocks are, therefore, essentially contemporaneous with the Highlandcroft series, and of probable Late Ordovician age.

OLIVERIAN PLUTONIC SERIES

Rocks of the Oliverian plutonic series of Middle (?) Devonian age crop out in a group of echelon domes east of and parallel to the Connecticut River. Some of the plutonic rocks intrude the Clough quartzite of Early and Middle Silurian age (Chapman, C. A., 1939, p. 168), and the effects of the emplacement of the domes are apparent in the Early Devonian Littleton formation. Billings (1937, p. 536) considers that the emplacement of the Oliverian domes predates the Acadian (?) regional folding and metamorphism and that the series is of Middle (?) Devonian age.

Age determinations for the Oliverian plutonic series are listed in table 2. Their average age (311 $\pm$ 26 million years) is in reasonably close agreement with the age set by the Committee on the Measurement of Geologic Time (1949-50) for the Middle Devonian (about 300 million years).

No well-dated localities in the northern Appalachians may be compared directly with the Oliverian plutonic series. The Monson gneiss of Massachusetts is, in part, the same plutonic unit (Hadley, 1949), but it is less well dated geologically than the equivalent rocks in New Hampshire. At the type locality in Monson, Massachusetts, the formation is clearly a paragneiss, unlike any of the plutonic series in New Hampshire. Marble (1950) has published an age of 390 million years for allanite (gravimetric analysis) from a pegmatite lens in the Monson gneiss at Greenwich, Mass. Inasmuch as this analysis is uncorrected for original lead, which is very probably present in allanite, the discrepancy between this date and that for the Oliverian (311 $\pm$ 26 million years) is not unexpected. Whether the Greenwich locality should be correlated with the Oliverian plutonic rocks or with the Bethlehem gneiss of the New Hampshire plutonic series is somewhat uncertain (Rodgers, 1952, p. 420), and geologically not important.

NEW HAMPSHIRE PLUTONIC SERIES

Stocks and batholiths of the New Hampshire plutonic series intrude the Early Devonian Littleton formation. None of these plutons cuts through Oliverian rocks, but on the basis of their internal structures they are regarded by Billings (1937, p. 12) as geologically younger than the Oliverian series, and contemporaneous with or slightly younger than the Acadian folding and metamorphism. A Middle or Late Devonian age, therefore, is favored (Billings, 1937, p. 506). From the data of table 3, the average age of the New Hampshire plutonic series is 296 $\pm$ 29 million years. It is, therefore, of approximately the same mean age as the Oliverian plutonic series (that is Middle (?) Devonian). Evidence favoring a Middle rather than Late Devon-

TABLE 3
Age Determinations on Minerals from the New Hampshire Plutonic Series

Formation	Location	Mineral[1]	α/mg/hr	Pb (ppm)	U (ppm)	Th calc. (ppm)	Th/U	c	k x 10^{-4}	Age (m.y.)
Kinsman quartz monzonite	Lovewell Mt. quadrangle	Zircon	248	28 (30,26)	620	242	0.4	2560	1.74	282
		Monazite	4351	720 (640,800)	1355	44,360	33.0	2065	0.61	337
Kinsman quartz monzonite	Cardigan quadrangle	Zircon	333	37 (36,38)	n.d.[2]	n.d.	—	2485	1.56	270
Bethlehem gneiss	Sunapee quadrangle	Zircon	242	30	500	679	1.4	2455	1.47	297
		Monazite	2922	470	2570	21,853	8.5	2180	0.87	346
		Xenotime	4053	530	798	43,280	54.0	2048	0.56	266
Bethlehem gneiss	Rumney quadrangle	Zircon	246	28	n.d.	n.d.	—	2485	1.56	277
Concord granite	Cardigan quadrangle	Monazite	2784	450	625	28,504	46.0	2052	0.58	329
Pegmatite in Concord granite	Cardigan quadrangle	Monazite	5285	700	n.d.	n.d.	—	2085	0.65	274
Concord granite	Concord quadrangle	Monazite	5352	830 (825,835)	n.d.	n.d.	—	2085	0.65	320
Winnipesauke quartz diorite[3]	Winnipesauke quadrangle	Zircon[4]	353	39 (38,40)	n.d.	n.d.	—	2485	1.56	269
		Zircon[5]	391	46.5 (45,47)	n.d.	n.d.	—	2485	1.56	285
Mean age										296
Standard deviation										29
Devonian										320-265 ± 10
Mean age, without uranium analyses										296 ± 30

[1] None of these materials is metamict.
[2] Not determined.
[3] Age determination by H. W. Jaffe.
[4] –80 + 200 mesh size crystals.
[5] –200 + 400 mesh size crystals.

ian age for both the Oliverian and New Hampshire plutonic series is pointed out below in the discussion of the granites from Maine and New Brunswick.

The determinations on the Bethlehem gneiss of the Sunapee quadrangle are noteworthy. There is reasonably good age agreement here for three different minerals from the same rock (303 ± 40 million years), each with its own alpha activity and lead content. This agreement offers independent support of the general validity of the Larsen method.

The well-known Ruggles pegmatite at Grafton, N. H., is geologically contemporaneous with the New Hampshire plutonic series. A chemical analysis of uraninite from the pegmatite (Shaub, 1938, p. 338) yielded an age of 305 million years (corrected by Rodgers, 1952, p. 415, to 310 million years). Mass spectrometric determination of the Pb 207/Pb 206 ratio of uraninite from the same pegmatite by Collins and others (1954, p. 10) yielded an age of 455 ± 160 million years. The first analysis has no correction for original lead; in the second analysis a large correction was made for original lead, but the isotopic composition of this lead was not accurately known. Both analyses would be consistent with the interpretation that the uraninite is no younger than 295 million years old.

The plutonic rocks and pegmatites of the New Hampshire plutonic series may probably be correlated with those in an area about Middleton, Connecticut (Rosenfeld and Eaton, 1956, p. 1823), where 15 chemical analyses of uraninite (uncorrected for original lead) from the pegmatites have yielded ages ranging from 270 to 300 million years (Rodgers, 1952, p. 414-415). Two Pb/U isotopic age determinations have also been reported from the district, one of these on samarskite from the Spinelli pegmatite, with an age of 260 million years (Rodgers, 1952, p. 413), and the other on uraninite from the Strickland pegmatite (Wasserburg et al, 1955) with an age of 267 million years. A K^{40}-A^{40} age of 274 million years has also been reported for the Strickland pegmatite, using an assumed branching ratio (Wasserburg et al, 1955). These isotopic ages are approximately 30-35 million years younger than the zircon-method age for the New Hampshire plutonic series. This discrepancy could possibly be explained by consistently high bias in the zircon age results (for unknown causes) or by real differences in the absolute ages of the rocks from both districts. It is conceivable, for example, that the Acadian diastrophism and the emplacement of granites and pegmatites in northern New England may have preceded that in southern New England.

The 260 million year age of the Spinelli samarskite has been accepted by Holmes (1946, p. 315) and the Committee on the Measurement of Geologic Time (1950, p. 18) as marking the close of the Devonian period. It should be pointed out that insofar as our geologic information is concerned, the samarskite could have a possible geologic age ranging from Middle Devonian to Middle Triassic.

Quinn and others (1957, table 3) have reported that some of the Devonian (?) granites of Rhode Island (i.e., the Scituate and others) have a mean age of 306 ± 18 million years, by zircon-method age determinations. These plutonic rocks are evidently of the same geologic age as the New Hampshire and Oliverian plutonic series.

TABLE 4

Absolute Age Determinations on Zircon from Plutonic Rocks of Southeastern New Hampshire and Southwestern Maine[1]

Formation	Location	Mineral	α/mg/hr	Pb(ppm)	c	k x 10^{-4}	Age (m.y.)
Binary granite of Fitchburg pluton (Billings, 1955)	Suncook quadrangle	Zircon	394	46.5 (45,48)	2485	1.56	286
Exeter diorite (of Hitchcock 1877)	Exeter quadrangle	Zircon	75	9.5 (9,10)	2485	1.56	307
Granite of the Biddeford series (of Katz, 1917)	Kennebunk, (Maine) quadrangle	Zircon[2]	348	43.5 (45,42)	2485	1.56	303
		Zircon[3]	410	47.5 (47,48)	2485	1.56	282
Mean age							294
Standard deviation							12
Devonian							320-265 ± 10

[1] Age determinations by H. W. Jaffe.

[2] −80 + 200 mesh size crystals.

[3] −200 + 400 mesh size crystals.

In both Massachusetts and Rhode Island there are granite series with mean zircon-method ages of approximately 260 million years (Webber and others, 1956, p. 580-581; Quinn and others, 1957). Among other types, granites of these series include representatives of the well-known Quincy alkalic granite. Granite of this petrologic type and geologic age is evidently not present in New Hampshire, and is apparently younger than the syntectonic Acadian granites.

PLUTONICS OF SOUTHEASTERN NEW HAMPSHIRE AND SOUTHWESTERN MAINE

Inasmuch as the geologic ages of the metamorphic formations in southeastern New Hampshire are uncertain (Billings, 1956, p. 99-105), there is similar uncertainty concerning the ages of the plutonic rocks that have invaded them. For this reason these plutonics have been indicated by a distinctive pattern on Billings' (1955) geologic map of New Hampshire, assigned to the Upper Devonian (?) and considered "probably [to] belong to the New Hampshire plutonic series" (Billings, 1955, map legend). Table 4 lists zircon-method ages for two plutonic rocks from southeastern New Hampshire and one from southwestern Maine. Their mean age (294 $\pm$ 12 million years) places them in the same age group as the New Hampshire plutonic series, and supports Billings' (1955) tentative geologic correlation.

The results of table 4 are of chief interest with relation to regional geologic problems. The listed plutonic formations locally cut through the metasedimentary Kittery, Eliot, and Berwick formations, (of Katz, 1917), whose equivalents in Massachusetts and southeastern New Hampshire constitute the Merrimack group (Hitchcock, 1878, p. 27; Billings, 1955, map legend). The age of all these formations is controversial. Katz (1917, p. 168-170), who named the Kittery, Eliot, and Berwick formations considered them to be of Carboniferous age; Freedman (1950, p. 487-489), on the other hand, concluded that the Eliot and Berwick formations (which are stratigraphically above the Kittery) are of probable Silurian age, because they seemingly underlie the Lower Devonian Littleton formation. The complex and conflicting geologic evidence on the age of the three formations has recently been admirably summarized by Billings (1956, p. 99-105). In view of the data of table 4, there now appears to be no question of their pre-Middle Devonian age.

There are two published age determinations on materials from the Fitchburg pluton, neither of which is in agreement with the data of table 4. A microanalysis of uraninite from the granite at Fitchburg, Massachusetts, by Hecht and Kroupa, quoted and corrected with new constants by Rodgers (1952, p. 419), yielded an age of 340 million years. Ignorance of the original lead content of the uraninite largely vitiates the value of this age determination. A single zircon-method age determination of 230 $\pm$ 25 million years was recently reported for the granite at Fitchburg, Mass. by Webber and others (1956, p. 580). The discrepancy between this age and that reported in table 4, (294 million years) may represent either experimental error in the data of table 4 or of Webber, or may possibly demonstrate that the petrographically complex Fitchburg pluton contains rocks belonging to more than one geologic interval. In defense of the data of table 4 it should be pointed out that the

TABLE 5

Age Determinations on Zircon from some Maine and New Brunswick Granites

Formation	Location	Mineral	α/mg/hr	Pb(ppm)	c	k x 10^{-4}	Age (m.y.)
Katahdin granite (of Toppan, 1932)[1]	Ripogenus Dam, Maine	Zircon	212 320	28 30	2485 2485	1.56 1.56	320 316
Granite[1]	5 mi. S. E. of Jackman, Maine	Zircon	315	43	2485	1.56	330
Granite[2]	do.	Zircon[3]	237	29.5 (29,30)	2485	1.56	302
		Zircon[4]	248	33 (33,33)	2485	1.56	322
St. George granite[1] (of Hayes and Howell, 1937)	New Brunswick	Zircon	363	45 (45,45)	2485	1.56	301

Mean age 315

Standard deviation 11

Devonian ..... 320-265 ± 10

[1] Determination by Jaffe on specimen collected by A. J. Boucot.

[2] Determination by Jaffe on specimen collected by J. W. Knox.

[3] Non-magnetic zircon.

[4] Slightly magnetic zircon.

binary granite on which the age determination was made is petrographically indistinguishable from the Concord granite, and was collected a mere 10 miles south-southeast of its type locality. In New Hampshire binary granites resembling the Concord are among the youngest members of the Fitchburg pluton (Billings, 1955, map legend).

SOME MAINE AND NEW BRUNSWICK GRANITES

Largely through the interest of A. J. Boucot of the U. S. Geological Survey in dating the Acadian orogeny in northern New England, four granites from Maine and New Brunswick were studied by the zircon method (table 5). The Katahdin granite of Toppan (1932) in north-central Maine, which is structurally on strike with the plutonic rocks of New Hampshire, has been dated geologically by Boucot (1954) as post-Early Devonian (i.e., post-Oriskany) and probably post-Acadian orogeny. It is a nonfoliated granite somewhat similar to the Concord granite of the New Hampshire plutonic series. The granite near Jackman, Maine, was sampled twice because it was originally thought to belong to a group of pre-Silurian granites in northwestern Maine. Recent field work near Jackman by Boucot and J. B. Thompson (verbal communication) indicates that this granite has intruded the Moose River sandstone (Lower Devonian) and has converted it to a hornfels. According to Boucot (verbal communication) the St. George granite of Hayes and Howell (1937) intrudes the Late Silurian Eastport formation and is unconformably overlain by the Perry formation, which contains Upper Devonian plant fossils and cobbles of the granite. As far as one can tell, all the granites of table 5 are probably of the same geologic age. As Boucot (1954, p. 148) has suggested, the evidence for a Middle Devonian age of both the granites and the Acadian orogeny is very compelling. There is also good reason for concluding that the granites from Maine and New Brunswick (in table 5) are essentially contemporaneous with the Oliverian and New Hampshire plutonic series of New Hampshire.

WHITE MOUNTAIN PLUTONIC-VOLCANIC SERIES

Stocks and ring dikes of the alkalic White Mountain plutonic-volcanic series postdate the Acadian folding and regional metamorphism and crosscut rocks of the older plutonic series. They have been assigned to the Mississippian (?) (Billings, 1945, p. 43) on the basis of the tentative correlation with the pre-Middle Pennsylvanian alkalic granites of eastern Massachusetts (Emerson, 1917, p. 186-187), but there is no field evidence proving this conclusively. Age data in table 7 fail to bear out this correlation and suggest instead that the White Mountain plutonic-volcanic series is probably of Late Permian or Early Triassic age. Variation diagrams of the alkalic granites of eastern Massachusetts (E. S. Lenker, verbal communication) have slightly different slopes than those of the White Mountain plutonic-volcanic series, which also indicates that the two rock series are probably unrelated.

Two sets of age determinations have been made on rocks of the White Mountain plutonic-volcanic series. Results of the first series of determinations (made in 1952-53) have been quoted in the literature (e.g. Faul, 1954, p. 267)

TABLE 6

Age Determinations on Zircon from the White Mountain Plutonic-Volcanic Series (1952)

Formation	Location	Mineral	α/mg/hr	Pb (ppm)	U (ppm)	Th (ppm)	Th/U	c	k x 10^{-4}	Age (m.y.)
Conway granite[1]	Redstone quarry	Zircon	1417	150	n.d.[2]	n.d.	—	2485	1.56	258
	North Conway		1050	105	n.d.	n.d.	—	2485	1.56	243
	quadrangle		1010	85	n.d.	n.d.	—	2485	1.56	198
			836	86	n.d.	n.d.	—	2485	1.56	251
Mt. Osceola granite[1]	Mt. Chocorua	Zircon	843	80	n.d.	n.d.	—	2485	1.56	232
	quadrangle		723	68	n.d.	n.d.	—	2485	1.56	230
			470	50	n.d.	n.d.	—	2485	1.56	259
Syenite[3]	Devil's Slide; Percy	Zircon	465	44	808	1945*	2.4	2385	1.30	223
	quadrangle	Chevkinite	995	98	186	10,000†	54.	2050	0.57	201
Mean age										233
Standard deviation										23
Carboniferous										265-210 ± 10
Mean age, without uranium analyses										234 ± 22

[1] Age determination by D. Gottfried on splits of zircon of different magnetic susceptibility.
[2] Not determined.
[3] Age determination by H. W. Jaffe (Jaffe and others, 1956).
* Th calculated
† Th determined

and for the sake of the record are here listed as table 6. Zircon was so plentiful in the Conway and Mt. Osceola granites that the zircon concentrates could be divided magnetically into several splits. In table 6 the more radioactive and more metamict zircon fractions were also the more magnetic fractions. The reason for concomitant increase in magnetism with radioactivity and degree of metamictization of the zircon is not understood.

In 1956 Jaffe, in the course of study of the effects of metamorphism on zircon-method ages, made several additional determinations on rocks of the White Mountain plutonic-volcanic series. The newer results (table 7) were strikingly at variance with the old, although each group of determinations is internally self-consistent. It is probable, therefore, that the first set of results was in error. Because of experience gained over the past few years, as well as the improved present practice of making replicate lead determinations and counting alphas for longer periods of time, the writers favor the results of table 7, (186 $\pm$ 14 million years), as more accurately representing the true age of the White Mountain plutonic-volcanic series. Fortunately isotopic age determinations for the Conway granite member of the series are currently in progress both at the Massachusetts Institute of Technology, the U. S. Geological Survey and at the Carnegie Institution laboratories in Washington.[1] Within a very short time it should be possible to check these results against those of tables 6 and 7.

If the results of table 7 accurately represent the age of the White Mountain plutonic-volcanic series (186 $\pm$ 14 million years), this age places the series very close to the presently-accepted date for the close of the Paleozoic (185 million years). The mean of the 21 determinations of tables 6 and 7 (206 $\pm$ 30 million years) would also place the series within the age limits currently assigned to the Permian (210-185 million years). On either basis it would appear that the series is of Permo-Triassic age, the likelihood being that it is Late Permian.

As has been indicated, there is virtually no geologic evidence on the age of the White Mountain plutonic-volcanic series, other than that it is post-Acadian. A pre-Late Triassic upper time limit is, however, suggested by the relations between the Cape Neddick gabbro (Wandke, 1922, p. 151) and the Agamenticus alkalic igneous complex (Wandke, 1922, p. 152; Woodard, 1957) near York, Maine. In view of the abundance of Late Triassic intrusives of basaltic and gabbroic affinities throughout New England, there is a strong probability that the Cape Neddick gabbro is of Triassic age. Woodard (1957, p. 63) states that the Agamenticus alkalic complex is probably a member of the White Mountain plutonic-volcanic series, and is definitely older than the Cape Neddick gabbro. Hence, a Late Permian, pre-Triassic age for the White Mountain series is likely.

The Monteregian Hills of southern Quebec consist of eight alkalic stocks intruded at intervals along a line extending 100 miles easterly from Montreal. The rocks are of post-Middle Devonian age, and have been assigned to the

[1] While this paper was in galley proof, Tilton, et al (Trans. Am. Geophysical Union, v. 38, p. 360-371) reported Pb/U, Rb/Sr and K/A isotopic ages for the Conway granite, the results showing remarkably excellent agreement at 185 million years.

TABLE 7

Additional Age Determinations on Zircon from the White Mountain Plutonic-Volcanic Series (1956)[1]

Formation	Location	Mineral	α/mg/hr	Pb(ppm)	c	k x 10^{-4}	Age (m.y.)
Monzodiorite	W. shore of Lake Winnipesauke, 2 mi. N. of W. Alton, N. H.	Zircon[2]	650	47 (46,48)	2485	1.56	180
		Zircon[3]	373	26.5 (26,27)	2485	1.56	177
		Zircon[4]	352	25 (24,26)	2485	1.56	176
		Zircon[5]	260	19 (18,20)	2485	1.56	182
		Zircon[6]	240	16.5 (16,17)	2485	1.56	171
Syenite from Mt. Ascutney	E. Slopes of Mt. Ascutney, Vt.	Zircon[4]	214	18.5 (20,17)	2485	1.56	211
		Zircon[6]	166	11.5 (11,12)	2485	1.56	172
Conway granite from Mt. Ascutney	E. Slopes of Mt. Ascutney, Vt.	Zircon[4]	373	26 (25,27)	2485	1.56	179
		Zircon[6]	247	20.5 (19,22)	2485	1.56	212
Conway granite (green phase)	E. end of green quarry Redstone, N. H.	Zircon[4]	298	22.5 (23,22)	2485	1.56	188
Mt. Osceola granite	Near dam of Franconia Paper Co.; Franconia quadrangle, N. H.	Zircon[4]	508	38.5 (38,39)	2485	1.56	188
		Zircon[6]	446	35 (33,37)	2485	1.56	195
Mean age							186
Standard deviation							14
Permian							210-185 ± 10

[1] Age determination by H. W. Jaffe.
[2] Magnetic zircon, –80 + 400 mesh size crystals.
[3] Slightly magnetic zircon, –200 + 400 mesh size crystals.
[4] Non-magnetic zircon, –200 + 400 mesh size crystals.
[5] Slightly magnetic zircon, –80 + 200 mesh size crystals.
[6] Non-magnetic zircon, –80 + 200 mesh size crystals.

Tertiary (?) by some geologists on the basis of the helium-method age of 57 million years reported by Urry (1936, p. 1218) on tinguaite from Mt. Royal, Montreal. Zircon from the essexite of Mt. Royal was concentrated and purified by E. S. Lenker of Dartmouth College in 1956, and its age measured by Jaffe and Waring. This determination (2323 α/mg/hr; 210, 215 ppm Pb; age 224 m.y.) places the Monteregian Hills in the Carboniferous. Whether this petrographic province is slightly older than the White Mountain plutonic-volcanic series is uncertain. Further determinations are obviously necessary. Because of the well-known difficulties inherent in the helium method, however, the odds that the Monteregian Hills are Late Paleozoic rather than Tertiary are overwhelming.

The White Mountain plutonic-volcanic series is evidently younger than the Westerly granite of Rhode Island which is known from geologic evidence to be Late Carboniferous or younger, and from zircon-method dating to have an age of 231 $\pm$ 16 million years (Quinn and others, 1957).

DISSCUSSION OF RESULTS

Larsen-method age determinations on the four plutonic series of New Hampshire have yielded the following data in millions of years: Highlandcroft 385 $\pm$ 27, Oliverian 311 $\pm$ 26, New Hampshire 296 $\pm$ 29, and White Mountain 186 $\pm$ 14 (or 206 $\pm$ 30). Middle Devonian granites of Maine and New Brunswick have a mean age of 315 $\pm$ 11 million years, and plutonics of southeastern New Hampshire and southwestern Maine have an age of 294 $\pm$ 12 million years. All standard deviations from the mean are within 10 percent of the average age and are believed due chiefly to inaccuracies in the measurement of lead content or of alpha activity, and to sample impurity.

Inasmuch as a series of radioactive determinations for any plutonic series will show variability, it is of some importance to examine the data statistically. One method is to apply the t test. The usual formula for the t test (Dixon and Massey, 1951, p. 97) may be rearranged as follows:

$$\mu = \frac{\bar{x}\sqrt{N} \pm ts}{\sqrt{N}}$$

$\bar{x}$ = mean value of sample

μ = population mean, the mean of an infinite number

s = standard deviation of the sample

N = number of observations in the sample

The statistic t may be read from the tables and is dependent upon the sample size. The value in the table is determined by the degrees of freedom (N-1) and the chosen confidence interval. To consider the median 90 percent of a series of values and discard the upper 5 and lower 5 percentages is spoken of as the 90 percent confidence interval. The t value at the lower 5 percent limit of our sample is indicated by $t_{0.05}$; that at the upper 95 percent limit by $t_{0.95}$. If t values are read from statistical tables for a given sample, it is then possible to calculate corresponding limits within which μ (the true mean) must lie. Results of such a calculation for the age determinations of this paper are listed in table 8. The μ values in table 8 are ages which, at the 90 percent confidence

TABLE 8

Geologic Ages Derived from Confidence Limits of Observed Mean Ages

Plutonic series	$\bar{x}$	s	N	$t_{0.05}$	$t_{0.95}$	μ (max.-min.)	Age range, permitted by radioactive determinations
Highlandcroft plutonic series	385	27	4	–2.35	2.35	417-353	Middle Ordovician—Middle Silurian
Oliverian plutonic series	311	26	5	–2.13	2.13	336-286	Late Silurian—Late Devonian
New Hampshire plutonic series	296	29	12	–1.80	1.80	311-281	Early Devonian—Late Devonian
Plutonics from southeastern New Hampshire and southwestern Maine	294	12	4	–2.35	2.35	308-280	Middle Devonian—Late Devonian
Granite from Maine and New Brunswick	315	11	6	–2.01	2.01	324-306	Late Silurian—Middle Devonian
White Mountain plutonic-volcanic series	186	14	12	–1.80	1.80	193-179	Late Permian-Early Triassic (Late Pennsylvanian—Late Permian)

level, represent maximum and minimum age values between which the true mean values of our samples must lie. We can assign no precise values for μ within these intervals, but we can reject the hypothesis that the true mean ages of each of our samples lie beyond their respective limits.

Although there is, as has been indicated, some reason for questioning some of the dates currently accepted by the Committee on the Measurement of Geologic Time (1950, p. 18) for the close of some of the periods during Paleozoic time, these dates nevertheless furnish a convenient framework of reference with which to compare the data of table 8 and the geologic facts.

The evidence from geologic methods that the Highlandcroft plutonic series is of Late Ordovician (?) age is good, and a date of 385 ± 27 million years would be consistent with the interpretation that this series was emplaced during the Taconic orogeny.

Overlap in the radioactive ages of the Oliverian plutonic series (311 ± 26 million years), the New Hampshire plutonic series (296 ± 29 million years), the Middle Devonian granites of Maine and New Brunswick (315 ± 11 million years), and the plutonic rocks of southeastern New Hampshire and southwestern Maine (294 ± 12 million years) indicates the essential contemporaneity of all these rocks. The μ values of table 8 demonstrate that these rocks can be no younger than approximately 280 million years (by the zircon method) and that there is, at best, a bare possibility that they fall within the age range currently assigned to the Late Devonian. The best explanation of the age and geologic data, first suggested by Boucot (1954, p. 148), is that the Acadian folding and emplacement of syntectonic plutons in northern New England is of Middle rather than Late Devonian age.

The Permian radioactive age of the White Mountain plutonic-volcanic series, (186 ± 14 million years), is in agreement with what is known of its areal geologic relations (post-Acadian orogeny and probably pre-Triassic). Unlike the Highlandcroft plutonic series, which reflects the Taconic orogeny, and the Oliverian and New Hampshire plutonic series, which reflect the Acadian orogeny, the White Mountain plutonic-volcanic series is apparently unrelated to a major deformational episode.

Geologic and radioactive age data now appear to indicate at least five Paleozoic plutonic series in New England. These would be, from oldest to youngest: (1) a series of Late Ordovician (Taconic) age—the Highlandcroft and equivalents—360 to 390 million years; (2) a series of Middle (?) Devonian (Acadian) age—the Oliverian, New Hampshire and equivalents—290-310 million years; (3) the pre-Pennsylvanian (Mississippian ?) alkalic granites of eastern Massachusetts—260 million years; (4) the post-Middle Pennsylvanian calc-alkalic granites of Rhode Island—230 million years; and (5) the Late Permian (?) alkalic White Mountain series 180-190 million years.

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LEAD-ALPHA AGES OF RHODE ISLAND GRANITIC ROCKS COMPARED TO THEIR GEOLOGIC AGES*

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ABSTRACT. Field studies have shown that there are at least three groups of granitic rocks in Rhode Island. The Scituate granite gneiss and the Esmond granite with their affiliates are oldest (Devonian? or older), the Cowesett granite and the Quincy granite are intermediate (Mississippian?), and the Westerly granite and the Narrangansett Pier granite or so-called redstone are youngest (late or post-Pennsylvanian). The two older groups are overlain unconformably by Pennsylvanian sedimentary rocks of the Narragansett Basin and the youngest group is intrusive into these Pennsylvanian rocks. The geologic evidence in Rhode Island does not give accurate indications of how much older or younger than the Pennsylvanian rocks these groups are. Lead-alpha age determinations on zircon and monazite from the three groups of granitic rocks gave mean ages of 306±18 MY (million years), 270±7 MY, and 234±23 MY, respectively. These ages are internally consistent, in agreement with the geologic evidence, and within the accepted age limits of the geologic time scale for the Devonian, Mississippian, and Pennsylvanian periods, respectively.

INTRODUCTION

The lead-alpha age determinations here discussed were made to find out how much agreement or disagreement there might be with ages previously arrived at on the basis of structural relations, stratigraphic evidence, and correlation. The geologic ages are taken chiefly from reports already published or in preparation, as part of a cooperative geological survey of Rhode Island by the Rhode Island Development Council and the U. S. Geological Survey. The contributions of Jaffe, Smith, and Waring to this study are part of a program conducted by the Geological Survey on behalf of the Division of Research of the U. S. Atomic Energy Commission.

Locations of samples are shown on figure 1.

All the granitic rocks discussed in this report are geologically younger than the Precambrian(?) Blackstone series. Most of them are older than the Pennsylvanian rocks of the Narragansett Basin.

Those rocks that are geologically younger than the Blackstone series and older than the Pennsylvanian rocks have been divided into two main groups. The older group has been assigned to a Devonian(?) or older age and includes the Scituate granite gneiss, alaskite, and augen gneiss. The younger group has been placed tentatively in the Mississippian system, and includes the Quincy granite and the Cowesett granite.

The youngest of the granitic rocks are intrusive into the Pennsylvanian rocks of the Narragansett Basin. They include two main types: (1) the Narragansett Pier granite or so-called redstone, a medium-grained rock exposed near the mouth of Narragansett Bay and westward along the south shore of Rhode Island, and (2) the Westerly granite, a fine-grained rock exposed mostly in the Carolina, Ashaway, and Watch Hill quadrangles (near Westerly and Bradford).

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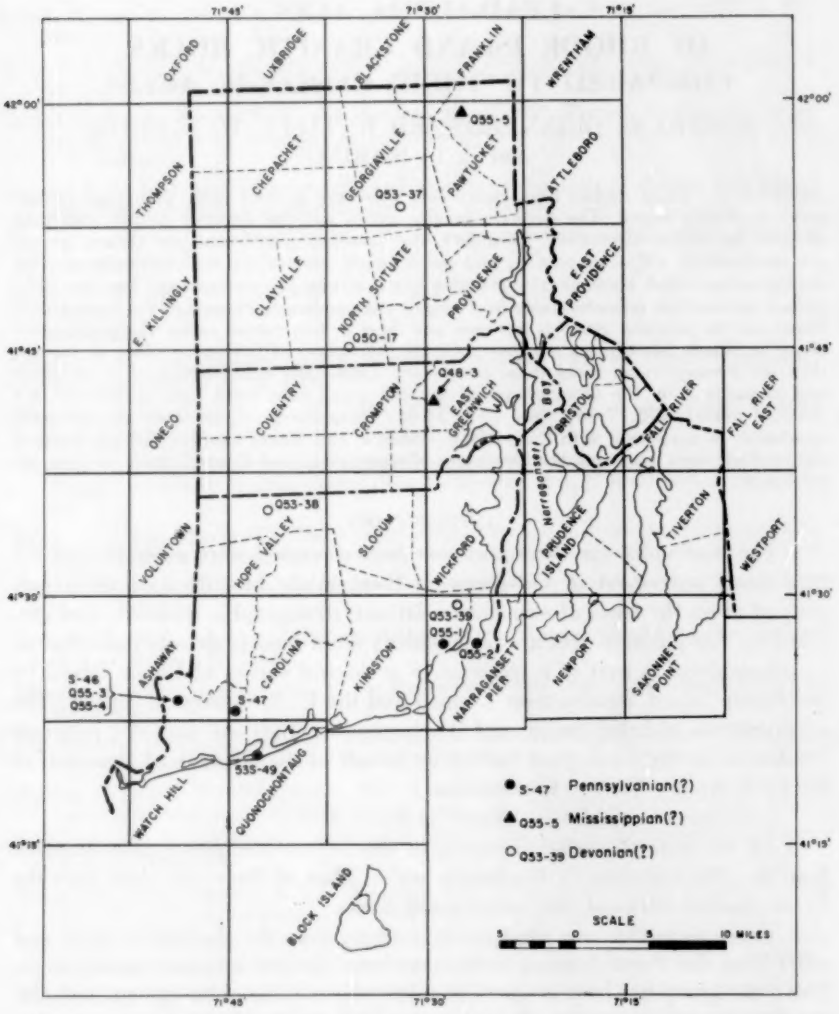

Fig. 1. Index Map of Rhode Island showing locations of samples and sample numbers.

Only the Pennsylvanian sedimentary rocks of the Narragansett Basin have been dated on the basis of fossils (Knox, 1944; Lesquereux, 1889; Round, 1924, 1927; Shaler, Woodworth, and Foerste, 1899).

PETROGRAPHY

Detailed petrographic descriptions of most of the Rhode Island granitic rocks are available in published reports, so only brief petrographic descriptions and a table of modes of the main types are presented here.

DEVONIAN(?) OR OLDER ROCKS

The Scituate granite gneiss is medium- to coarse-grained and slightly gneissic. The main constituents are microcline-microperthite, albite (An_9), quartz, biotite, and hornblende. Minor and accessory constituents are zircon, apatite, keilhauite (Young, 1938), allanite, magnetite, garnet, and epidote.

The alaskite facies is medium-grained and is characterized by a linear arrangement of quartz grains. The main constituents are microcline, oligoclase (An_{15}), quartz, and biotite. Minor and accessory constituents include zircon, apatite, magnetite, muscovite, and leucoxene.

The augen gneiss is fine-grained with phenocrysts commonly as much as 1 cm across and has a pronounced foliation. The main constituents are oligoclase (An_{20}), microcline-microperthite, quartz, and biotite. Minor and accessory constituents are hornblende, muscovite, keilhauite, apatite, zircon, magnetite, allanite, a carbonate mineral, and epidote.

MISSISSIPPIAN(?) ROCKS

The Quincy granite is medium-grained and massive. It consists chiefly of microperthite, quartz, riebeckite, and aegirite. The plagioclase is almost entirely included in the microperthite (Tuttle, 1952, p. 115). Minor and accessory constituents include sphene, zircon, a carbonate mineral, fluorite, magnetite, and astrophyllite.

The Cowesett granite is medium-grained and massive. The main constituents are microcline-microperthite, oligoclase (An_{11}), quartz, and biotite. Minor and accessory constituents include muscovite, zircon, apatite, magnetite, allanite, and fluorite.

LATE PENNSYLVANIAN OR POST-PENNSYLVANIAN ROCKS

The Narragansett Pier granite, also known in the Westerly area as the redstone granite, is medium-grained and massive to faintly gneissic. The main constituents are oligoclase (An_{25}), microcline, quartz, and biotite. Minor and accessory constituents include muscovite, magnetite, ilmenite, zircon, apatite, pyrite, sphene, and allanite; Smith and Cisney (1956) list also uranoan thorianite, bastnaesite, and monazite.

The Westerly granite is fine-grained and massive. The main constituents are oligoclase (An_{20}), microcline, quartz, and biotite. Minor and accessory constituents are muscovite, apatite, zircon, sphene, magnetite, fluorite, and monazite. This rock was the subject of an intensive chemical and petrographic study (Fairbairn and others, 1951) and of earlier petrographic studies (Chayes, 1950, and Quinn, 1943).

GEOLOGIC EVIDENCE OF AGES

DEVONIAN(?) OR OLDER ROCKS

Included among the Devonian(?) or older rocks are the Esmond granite with its affiliated rocks, and the group of granites and gneisses related to the Scituate granite gneiss, many of which were formerly included in the Sterling granite gneiss.

The Esmond granite has been intruded by the Mississippian(?) Quincy granite (Quinn, Ray, and Seymour, 1949), and boulders of it are contained

TABLE 1
Modes of Main Types of Granitic Rocks
of Rhode Island in Percent by Volume

Rock	Quartz	Potassic feldspar	Plagioclase	Biotite	Riebeckite & aegirite	Muscovite	Accessories	
Westerly granite Smith Quarries 1 Chayes (16 sections)	27.5	35.4	31.4 An_{20}	3.2		1.3	1.2	Late Pennsylvanian or Post-Pennsylvanian
Westerly granite Westerly area 2 Chayes (11 sections)	27.8	32.9	32.7	3.7		1.9	1.0	
Westerly granite Westerly area 3 Lundgren (15 sections)	27.5	32.0	34.4	3.9		1.4	.8	
Westerly granite Bradford 4 Chayes (5 sections)	23.1	27.1	40.8	6.3		1.4	1.3	
Westerly granite Bradford 5 Winslow (5 sections)	23.1	26.6	41.2	6.5		1.4	1.2	
Narragansett Pier granite Q37-51R	31	28	35 An_{25}	4		1	1	
Narragansett Pier granite Q55-1	35	24	28 An_{20}	7		5	1	
Cowesett granite Q48-3	21	49	24 An_{11}	3		2	1	Mississippian(?)
Quincy granite Q55-5	37	56			6		1	
Scituate granite gneiss Q50-17	25	44	27 An_{9}	3			1	Devonian(?) or older
Alaskite gneiss Ca 113	31.3	34.4	31.3 An_{25}	2.5			.5	
Augen gneiss Q53-38	30.4	28.6	35.0 An_{20}	5.0			1.0	

1. Westerly granite, standard sample G-1 (Fairbairn and others, 1951), mode by Chayes.
2. Westerly granite from several quarries in Westerly area (Chayes, 1950, p. 384).
3. Westerly granite from several quarries in Westerly area; mode by L. W. Lundgren, part of senior thesis at Brown University.
4. Westerly granite from Bradford (Chayes, 1950, p. 384).
5. Westerly granite from Bradford; mode by Marcia Ring, now Mrs. John D. Winslow, part of senior thesis at Brown University.

Q37-51R. Narragansett Pier granite in quarry 0.50 mile northwest of Chapman Pond, Ashaway quadrangle, mode by Quinn.

Q55-1. Narragansett Pier granite intrusive into Pennsylvanian sedimentary rocks at south end of Tower Hill, Narragansett Pier quadrangle, mode by Quinn.

Q48-3. Cowesett granite, East Greenwich quadrangle, on Cowesett Road, 3100 feet east of Quaker Lane, mode by Quinn.

Q55-5. Quincy granite, Pawtucket quadrangle, Beacon Pole Hill 400 feet west of bench mark, mode by Quinn.

Q50-17. Scituate granite gneiss, North Scituate quadrangle, west abutment Kent (Gainer Memorial) Dam, mode by Quinn.

Ca 113. Alaskite gneiss, Carolina quadrangle, southwest slope Kenyon Hill, mode by G. E. Moore, Jr.

Q53-38. Augen gneiss, Hope Valley quadrangle, Ten Rod Road, 2800 feet east of West Exeter, mode by G. E. Moore, Jr.

in conglomerate of Pennsylvanian age (Richmond, 1952). No evidence is available in Rhode Island to show how much older the Esmond granite is than the Quincy granite, but the mineral composition seems to relate it to the Scituate granite gneiss.

The Sterling granite gneiss was assigned to a late or post-Carboniferous age by Loughlin (1910) and Emerson accepted that age assignment (Emerson, 1917). The evidence on which this was based was the supposed gradation and equivalence of the Sterling granite gneiss with rocks that clearly intrude the Pennsylvanian rocks near the mouth of Narragansett Bay and the absence of pebbles of the Sterling granite gneiss in conglomerate of Pennsylvanian age. The gradation and equivalence were not supported by more recent studies, and the lack of Sterling granite gneiss pebbles in conglomerates of Pennsylvanian age can be explained otherwise.

Richmond (1952) and Quinn (1951) described a contact where the pre-Pennsylvanian Esmond granite is intrusive into the Sterling granite gneiss; this obviously implies a pre-Pennsylvanian age for this facies of the Sterling granite gneiss. Because of this difference of interpretation of age and because of the great variety of rocks included in the Sterling granite gneiss, Quinn gave the name Scituate granite gneiss to part of the Sterling granite gneiss (Quinn, 1951). Subsequent mapping has distinguished an alaskite gneiss and an augen gneiss that are probably related to the Scituate granite gneiss (Moore, written communication concerning Hope Valley quadrangle; Nichols, 1956; Power, personal communication concerning the Slocum quadrangle). The alaskite gneiss seems to be the same age as the Scituate granite gneiss and the augen gneiss seems to be younger (Moore, written communication). Samples Q50-17 and Q53-37 are of the Scituate granite gneiss, Q53-38 is of the augen gneiss, and Q53-39 is of the alaskite gneiss.

MISSISSIPPIAN(?) ROCKS

In the northern part of Rhode Island there are several areas of riebeckite-aegirite granite that is correlated with the Quincy granite of Massachusetts. An affiliated granite porphyry has yielded boulders to conglomerate of Pennsylvanian age of the Norfolk Basin (Emerson, 1917, p. 188). Emerson stated that the Quincy granite is intrusive into Devonian(?) rocks (p. 188). Sample Q55-5 taken in Rhode Island did not yield enough zircon for a reliable age determination, so QG-1 from near Peabody, Mass., is included in table 2.

The Cowesett granite of similar age has been mapped in the East Greenwich quadrangle (Quinn, 1952). This granite intrudes the Spencer Hill volcanics, which contain fragments of the Esmond granite and which are overlain unconformably by Pennsylvanian sedimentary rocks. The Cowesett granite does not contain riebeckite or aegirite, as does the Quincy granite, but the geologic relations are similar and it has associated with it veinlets of dark purple fluorite like those associated with the Quincy granite in northern Rhode Island. Sample Q48-3 is of the Cowesett granite.

LATE PENNSYLVANIAN OR POST-PENNSYLVANIAN ROCKS

Along the shore in the Narragansett Pier quadrangle there are numerous pegmatite dikes intrusive into the Pennsylvanian sedimentary rocks (Nichols,

1956). Further southward medium-grained granite is also intrusive into the considerably metamorphosed Pennsylvanian rocks. At the locality of Q55-1 (south end of Tower Hill) there are several sills of granite intrusive into the rocks of Pennsylvanian age. This granite is similar to the Narragansett Pier granite extensively exposed along the shore 2 miles southeast and to the so-called redstone of the quarries in the Ashaway quadrangle, except that the granite sills contain more muscovite and are not pink. At the locations of samples S-47 and Q55-3 (Bradford and Westerly) there are dikes of fine-grained granite, the Westerly granite, which are intrusive into the medium-grained Narragansett Pier granite. Both the medium-grained and the fine-grained granite were intruded after the Pennsylvanian sedimentary rocks had been folded and metamorphosed, presumably in the late stages of the Appalachian orogeny. Sample Q55-2, from the shore 2¼ miles east of Q55-1, was taken from granite intrusive into Pennsylvanian rocks, but it did not yield enough zircon for an age determination. Samples S-46 and Q55-3 are of the Narragansett Pier granite in the Ashaway quadrangle (north of Westerly). Sample 53S-49 was taken from the beach of the Quonochontaug quadrangle and seems to be the Narragansett Pier granite, but the rock there contains schlieren and inclusions. Samples S-47 and Q55-4 are of the fine-grained Westerly granite.

ORIGIN AND METAMORPHISM OF THE GRANITIC ROCKS

Quinn (1951) has described evidence of a magmatic origin of the Scituate granite gneiss in the North Scituate quadrangle, although there is also a border facies of replacement origin. Moore has observed evidence in the Hope Valley quadrangle (written communication) of magmatic flow structure of the augen gneiss of sample Q53-38. Augen gneiss of somewhat similar appearance in the Narragansett Pier quadrangle (Nichols, 1956) and in the Slocum quadrangle (Power, written communication) shows evidence of a replacement origin. Moore has also observed magmatic flow structure in the alaskite gneiss in the Carolina quadrangle (written communication). Sample Q53-39 is from alaskite gneiss in the Narragansett Pier quadrangle where there is no evidence of either magmatic or replacement origin.

The Quincy granite of northern Rhode Island is in partly concordant intrusions of probable magmatic origin (Quinn, Ray, and Seymour, 1949). The geologic relations of the Quincy granite near Peabody, Mass. (sample QG-1), were not studied by the present authors. The Cowesett granite in the Crompton quadrangle appears to have been intruded as a magma, as is evidenced by the spreading apart of schist layers by granite stringers.

The Late Pennsylvanian or post-Pennsylvanian granitic rocks of the Narragansett Pier quadrangle are of magmatic origin (Nichols, 1956). Rotated inclusions of schist in the granite of the Ashaway quadrangle indicate a magmatic origin there also.

Most of these granitic rocks show little obvious effect of metamorphism. The Devonian(?) and Mississippian(?) rocks were undoubtedly present during the Appalachian orogeny; the Devonian(?) rocks may have been intruded during the last stage of the Acadian orogeny. The Appalachian orogeny caused

is determined in an ionization chamber receiving a continuous flow of argon.

almost no metamorphism in the northern part of the Narragansett Basin, but caused the formation of staurolite-garnet schists and mica schists in the southern part. The Devonian(?) and Mississippian(?) granitic rocks show some granulation and local shear zones. Muscovite, in minor amounts, is the only metamorphic mineral in these granitic rocks. The gneissic structure is partly due to magmatic flow, although some of it may be a relict structure resulting from metasomatism. The Late Pennsylvanian or post-Pennsylvanian rocks show no effects of metamorphism.

LEAD-ALPHA AGE DETERMINATIONS

Method.—The lead-alpha method for determining the age of accessory minerals of igneous rocks was first described by Larsen, Keevil, and Harrison (1952). Since publication of their paper, some 400 age determinations have been made of zircon, monazite, and xenotime from igneous rocks under investigation by geologists of the U. S. Geological Survey. The age determinations are, for the most part, in good agreement with field relations for those rocks for which there is good geologic control (Jaffe, Gottfried, and Waring, 1955). The method is based on the fundamental assumption that there is no significant amount of original lead of crystallization in zircon and that all the lead present has been produced by decay of uranium and thorium present in the zircon at the time of crystallization. The Pb^{+2} ion, ionic radius = 1.32 Å, is much too large to substitute freely for the much smaller Zr^{+4} ion, ionic radius = 0.87 Å, in the zircon lattice. In addition to the size difference, such substitution would require a complex coupled substitution to balance the loss in charge that would occur if a bivalent ion were to replace a quadrivalent ion. It is also assumed that no uranium, thorium, or lead has been removed from or added to the zircon since its crystallization from a magma. For this reason, mineralized rocks and highly metamorphosed igneous rocks are generally avoided in the collection of samples for age determination. The age is calculated from the formula, $t = \frac{c \times Pb\ (ppm)}{\alpha/mg/hr}$ where t = age in millions of years (MY), Pb is the lead content in parts per million, α is alpha counts (per milligrams per hour), and c is a constant equal to 2632 if all the alpha activity is due to uranium, and to 2013 if all the alpha activity is due to thorium. The values for c used in this report are 2485 for zircon, assuming a Th/U ratio of approximately 1, and 2085 for monazite, assuming a Th/U ratio of approximately 25. Where t is greater than 200 MY, a correction is made for the parent decay of U and Th using the formula:

$$T = t - \tfrac{1}{2}\, kt^2$$

where T = age in MY corrected for parent decay of uranium and thorium, k = a decay constant = 1.56×10^{-4} for zircon and 0.65×10^{-4} for monazite based upon assumed Th/U ratios of approximately 1 and 25, respectively. The choice of these values for c and k made without benefit of uranium and thorium analyses, will yield a maximum possible error of approximately 7 percent in the age if the assumed Th/U ratios are seriously in error. Alpha counts are made on 60-mg samples of hand-picked zircon ground to –400 mesh size. The powder is packed into a planchet with a 1.0-cm diameter and the alpha activity

is determined in an ionization chamber receiving a continuous flow of argon. The lead is determined in duplicate spectrographically (Waring and Worthing, 1953) on part of the same 60-mg sample on which the alpha count is determined. The alpha and the lead determinations are believed to be accurate to ± 5 and ± 10 percent, respectively. The method is described more fully by Gottfried, Senftle, and Jaffe (1955 and personal communication).

It has been observed that the zircon crystals tend to be freed from the rocks in grinding and generally are not broken during the processing of the rock. There is often a tendency for the alpha activity to increase inversely with crystal size, providing an opportunity for obtaining duplicate or triplicate age determinations on otherwise homogeneous zircon from the same rock. This is shown in table 2, where three determinations were obtained on zircon from the Cowesett granite. The three size fractions used were −100+200 mesh, −200+400 mesh, and −400 mesh; the zircons of the three size fractions were not crushed fragments of larger crystals but were euhedral, doubly terminated, crystals of different crystallization size. Although the alpha activity of each size fraction increased inversely with crystal size, the lead showed a corresponding increase, and the lead-alpha ratios of the three fractions from the Cowesett granite yielded ages of 272, 272, and 257 MY (million years), in good agreement.

Ages determined on different minerals from the same rock also provide a check on the method. Zircon and monazite separated from two samples of the Westerly granite, for example, gave ages of 243 and 220 MY, respectively (table 2), agreeing within ± 10 percent. Precise limits of error for the method will have to await results of isotopic analyses of minerals from rocks of known geologic age. In general, the age determination of one rock from an area is an unsatisfactory practice and the result may be subject to a large error, whatever method is used. When several determinations are made on a sequence of consanguineous rocks, the lead-alpha method generally yields results which agree within ± 10 percent or 10 MY of the mean value, whichever is the greater.

The most difficult phase of the lead-alpha age determination is the final purification of the zircon rather than the alpha or lead measurements. Lead-bearing minerals such as molybdenite, pyrite, and barite, although present in trace quantities in granitic rocks are concentrated with zircon and may contribute more lead than is in the zircon. For this reason, all samples must be hand-picked free of these impurities before age determinations are made by the lead-alpha or any other method.

Results.—Sixteen age determinations were made on zircon and monazite from eleven granitic rocks from Rhode Island and one from Massachusetts. The results of the determinations are given in table 2. The mean ages of 306 ± 18, 270 ± 7, 234 ± 23 MY, respectively, are internally consistent, in agreement with field relations of the rocks of the three geologic age groups, and within the time limits set for the Devonian, Mississippian, and Pennsylvanian periods (Committee on the Measurement of Geologic Time, 1949-50). These relationships are shown in figure 2.

The alkalic character of the Quincy granite and its associated volcanics has long been taken as evidence that these rocks are to be correlated with the

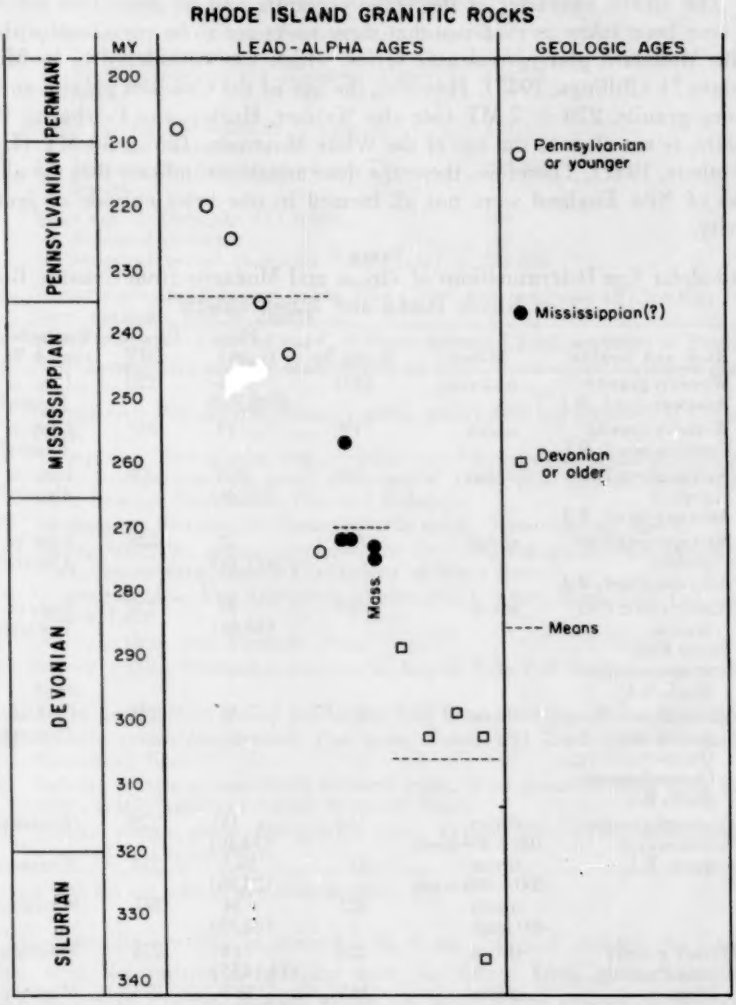

Fig. 2. Graph comparing lead-alpha age determinations with geologic ages. Details are contained in table 2. Different ages in same vertical line are of same sample.

Correlations.—A correlation of the Scituate granite gneiss and its associates with the new Hampshire plutonic series of Late Devonian(?) age seems plausible on the basis of petrographic characters, structural habit, and geologic relations. The mean ages of 306 ± 18 MY for the Scituate granite gneiss with its related rocks and 296 ± 29 MY for the New Hampshire plutonic series (Lyons and others, 1957) are in good agreement with this correlation. The New Hampshire plutonic series is considered to be Late Devonian(?) (Billings, 1955, New Hampshire geologic map.)

TABLE 2 (Continued)

Mean age for late or post-Pennsylvanian rocks	234

The alkalic character of the Quincy granite and its associated volcanics has long been taken as evidence that these rocks are to be correlated with the White Mountain plutonic-volcanic series, which was considered to be Mississippian(?) (Billings, 1945). However, the age of the Cowesett granite and the Quincy granite, 270 ± 7 MY (see also Webber, Hurley, and Fairbairn, 1956, p. 580), is not close to the age of the White Mountain, 186 ± 14 MY (Lyons and others, 1957). Therefore, these age determinations indicate that the alkalic rocks of New England were not all formed in one brief episode of igneous activity.

TABLE 2

Lead-alpha Age Determinations of Zircon and Monazite from Granitic Rocks of Rhode Island and Massachusetts

Field No.	Rock and locality	Mineral	α/mg/hr	Pb (ppm)	Pb-α Age MY	Probable geologic age (A.W. Quinn)
Q55-4	Westerly granite Ashaway quad., R.I.	monazite	5494	585 (580,590)	220	Late or post-Pennsylvanian
S-47	Westerly granite Carolina quad., R.I.	zircon	190	19	243	Late or post-Pennsylvanian
Q55-3	Narragansett Pier granite Ashaway quad., R.I.	zircon	300	25.5 (25,26)	208	Late or post-Pennsylvanian
S-46	Narragansett Pier granite Ashaway quad., R.I.	zircon	304	28 (27,29)	225	Late or post-Pennsylvanian
Q55-1	Narragansett Pier granite Tower Hill, Narragansett Pier quad., R.I.	zircon	509	49 (48,50)	235	Late or post-Pennsylvanian
53S-49	Narragansett Pier granite at Quonochontaug, Quonochontaug quad., R.I.	zircon	515	58	274	Late or post-Pennsylvanian
Q48-3	Cowesett granite E. Greenwich quad., R.I.	zircon −100+200 mesh	134	15 (14,16)	272	Mississippian
		zircon −200+400 mesh	217	24.5 (24,25)	272	Mississippian
		zircon −400 mesh	322	34 (33,35)	257	Mississippian
QG-1	Quincy granite near Peabody, Mass.	zircon	124	14 (14,14,15)	275	Mississippian
		zircon	165	18.5 (18,18,18,20)	273	Mississippian
Q53-38	Augen gneiss Hope Valley quad., R.I.	zircon	151	18	289	Devonian
Q53-39	Alaskite gneiss Narragansett Pier quad., R.I.	zircon	800	100	303	Devonian
Q50-17	Scituate granite gneiss N. Scituate quad., R.I.	zircon	146	18	299	Devonian
Q53-37	Scituate granite gneiss	zircon	251	35	337	Devonian
	Georgiaville quad., R.I.	zircon	352	44	303	Devonian

geologic periods falling within a time interval of less than 100 MY, demonstrates the utility of the method.

	Mean age for late or post-Pennsylvanian rocks	234
	Standard deviation	23
	Pennsylvanian period (Geologic Time Scale)	210-235
	Mean age for Mississippian (?) rocks	270
	Standard deviation	7
	Mississippian period (Geologic Time Scale)	235-265
	Mean age for Devonian (?) rocks	306
	Standard deviation	18
	Devonian period (Geologic Time Scale)	265-320
Q55-4	Westerly granite, Ashaway quad., quarry 3400 feet northwest of Chapman Pond, lower northeast part of quarry.	
S-47	Westerly granite, Carolina quad., Sullivan quarry, 1.2 mi. southeast of Bradford.	
Q55-3	Narragansett Pier granite, same quarry as Q55-4, from upper southwest part of quarry.	
S-46	Narragansett Pier granite, Ashaway quad., quarry 3400 feet northwest of Chapman Pond.	
Q55-1	Narragansett Pier granite sills intrusive into Pennsylvanian schist and conglomerate, Narragansett Pier quad., south end of Tower Hill, ¼ mile north of traffic circle between Narragansett Pier and Wakefield.	
53S-49	Narragansett Pier granite, Quonochontaug quad., Quonochontaug Beach.	
*Q55-2	Narragansett Pier granite intrusive into Pennsylvanian schist, Narragansett Pier quad., Boston Neck, shore 0.47 mile west of Whale Rock.	
Q48-3	Cowesett granite, East Greenwich quadrangle, Cowesett Road, 3100 feet east of Quaker Lane.	
QG-1	Quincy granite, near Peabody, Mass.	
*Q55-5	Quincy granite, Pawtucket quadrangle, Beacon Pole Hill 400 feet west of bench mark.	
Q53-38	Augen gneiss, Hope Valley quad., Ten Rod Road, 2800 feet east of West Exeter.	
Q53-39	Alaskite gneiss, Narragansett Pier quad., Tower Hill Road, 2500 feet south of Mooresfield Road.	
Q50-17	Scituate granite gneiss, North Scituate quad., West abutment Kent Dam (since 1949 officially known as Gainer Memorial Dam).	
Q53-37	Scituate granite gneiss, Georgiaville quad., Farnum Pike, 1200 feet southeast of west end of Capron Road.	

*Samples that did not give an age determination.

These results are also in accord with those obtained recently by Roques (1956) who determined lead-alpha ages on zircon from a Carboniferous granite massif in France. Roques states (p. 529), "The granite of Mayet de Montagne is a porphyritic granite to a biotite monzonite. It was chosen, to test the usefulness of the age method, because of its well established upper Carboniferous age." Roques, using the lead-alpha method, obtained results of 220 MY, 200 MY, and 206 MY on zircon from three samples of the massif collected at intervals of several kilometers. The mean age, 209 ± 10 MY, for upper Carboniferous, is in good agreement with the lead-alpha results obtained by other investigators on Carboniferous rocks from New England, except the White Mountain plutonic-volcanic series. These are compared in table 3, along with the summary results obtained on Devonian rocks from several New England localities. The consistency of the lead-alpha ages, for consecutive

to indicate that the Narragansett Pier and Westerly granites were intruded during the Pennsylvanian period. Apparently the Appalachian orogeny began

strates the utility of the method.

TABLE 3

Lead-alpha Ages of Devonian and Carboniferous Granitic Rocks of France, Rhode Island, New Hampshire, Maine, and New Brunswick, Canada

Area	No. of determinations	Pb/α age MY Standard deviation	Geologic age and authority	
Mayet de Montagne, France (granite-monzonite)	3	209 ± 10[1]	Carboniferous ("Upper")	Roques, 1956 Jung and others, 1939
Rhode Island, Westerly granite, Narragansett Pier granite, and related rocks	6	234 ± 23[3]	Carboniferous or post-Carboniferous (Pennsylvanian)	Quinn, this paper Nichols, 1956
New Hampshire, White Mountain plutonic-volcanic series	12	186 ± 14[2]	Carboniferous (Mississippian?)	Billings, 1945
Rhode Island and Massachusetts, Cowesett and Quincy granites	5	270 ± 7[3]	Carboniferous (Mississippian?)	Quinn, this paper
New Hampshire, New Hampshire plutonic series	12	296 ± 29[2]	Late Devonian(?) (Late Devonian?)	Billings, 1955 Lyons and others, 1957
Northern Maine, presumably New Hampshire plutonic series	5	318 ± 10[4]	Devonian (?) (Late Devonian?)	Boucot, verbal communication
St. George, New Brunswick, Canada	1	301 [2]	Devonian (Acadian)	Boucot, verbal communication
Rhode Island, Scituate granite gneiss and related rocks	5	306 ± 18[3]	Devonian(?)	Quinn, this paper

[1] Pb/α ages determined by Roques and Panguad (Roques, 1956)
[2] Pb/α ages determined by Jaffe and Waring (Lyons and others, 1957)
[3] Pb/α ages determined by Jaffe and Waring (Quinn and others, this paper.)
[4] Pb/α ages determined by Jaffe, Lyons, Knox and Waring (Lyons and others, written communication)

CONCLUSIONS

These age determinations show remarkably good agreement with the geological evidence that had been assembled before this method of age determination had been developed. This agreement applies to most local evidence of relative age and to most regional correlations.

The Scituate granitic rocks at 306 MY seem to be of Devonian age and presumably were emplaced during the Acadian orogeny. This supports the recently described evidence of a pre-Pennsylvanian age and is in disagreement with the previous assignments to a late or post-Pennsylvanian age.

The geological evidence indicates that the Quincy and Cowesett granites are probably Mississippian. The age 270 MY indicates that they may be late Devonian or early Mississippian.

The mean of the age determinations of the Narragansett Pier and Westerly granites is 234 MY, but the spread between ages of this group is too large to allow this to be considered an accurate age. However, the evidence appears

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Knox, A. S., 1944, A Carboniferous flora from the Wamsutta formation of southeastern

during the Pennsylvanian period. Apparently the Appalachian orogeny began early in New England. Indeed, the very coarse conglomerates of the Narragansett Basin show that neighboring areas were uplifted several times while the basin was being filled with sediments in early or middle Pennsylvanian time.

Although sequences of related rocks yield consistent mean ages by the lead-alpha method, individual results reveal some limitations of the method. Thus, the rock at Quonochontaug (53S-49) with an age of 274 MY is close to both the Devonian(?) and the Mississippian(?) sequences, but the petrographic characters relate it to the Pennsylvanian sequence. This rock shows some evidence of contamination.

An additional inconsistency is shown by the relation of sample Q55-4 of the Westerly granite and Q55-3 of the Narragansett Pier granite, both from the same quarry. Intrusive relations show the Westerly to be younger than the Narragansett Pier granite but the age determinations indicate the Narragansett Pier to be younger, with an age of 208 MY compared to 220 MY for the Westerly. Such a reversal of ages is within an error of $\pm$ 5 percent and is within the probable error of the method. Actually it seems probable that these two types of granite were almost contemporaneous.

In addition to the above discrepancies of individual ages, some of the samples collected did not yield enough zircon or monazite for a determination of their ages.

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known as "pipe-clay". During arid summers this carbonate sediment forms a hard white surface on the dry beds of the lakes, especially those which were formerly the southward continuation of the Coorong. Similar sediment also

OF SOUTH AUSTRALIA

A. R. ALDERMAN and H. CATHERINE W. SKINNER

ABSTRACT. Fine dolomite-calcite sediments of Pleistocene to Recent age occur over a wide area in the South-East province of South Australia. Similar sediments are being formed in a number of saline lakes and in a shallow inlet of the sea. The origin of the dolomitic sediments is ascribed to elevated pH caused by plant growth in shallow saline water.

INTRODUCTION

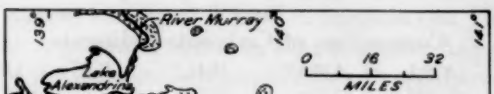
The physiography of the South-East province of South Australia is dominated by a series of ranges of consolidated sand dunes. They trend NNW parallel to the present coast and are separated by long flat interdunal areas. The ranges represent former coastal dunes left stranded during Quaternary time by the retreating sea. The latest phase of this is to be seen where the Coorong, a long and narrow stretch of sea water, is separated from the open sea by Younghusband Peninsula, a strip of sand dunes. At its southern end a former extension of the Coorong is now represented by a series of lakes and lagoons from which the sea has retreated and which indicate the similar origin of the interdunal areas further inland.

The surface rocks of the region are predominantly carbonates. Limestones of Early to Middle Tertiary age, which are partly dolomitic, outcrop over wide areas in the south and apparently underlie the Pleistocene and Recent marine and freshwater sediments and dune rocks of the central and northern parts of the province. The widespread and prominent dunes consist of varying proportions of quartz sand and shell fragments and are mostly capped by a layer of kunkar limestone. The geology of the region has been discussed by Hossfeld (1950) and Sprigg (1952).

The main drainage of the whole region is underground. Meteoric waters disappear very rapidly in the dunal areas either by penetration or by surface run-off from the kunkar. The flat interdunal areas are however relatively impervious and lead to the development of swamps and shallow lakes after rain. Some lakes are permanent but others are shallow and generally become dry during the summer season.[1] Water plants, the most abundant being *Ruppia maritima* Linn., and a fauna of which copepods and small molluscs are the most obvious members, regenerate in the intermittent lakes during the winter and populate the permanent lakes throughout the year.

The sediment from one of these intermittent lakes, situated 10 miles north of Kingston and referred to in this paper as "Kingston Lake," was found by Sir Douglas Mawson (1929) to consist largely of dolomite. A recent examination of similar material from the same locality shows that it is a very fine aggregate of dolomite and calcite with some halite and small amounts of quartz and clay minerals. Sediments of this nature which are extremely fine-grained and possess marked plastic properties when wet have been locally

[1] The average annual rainfall varies from 15 inches in the north to 34 inches in the south. Kingston has an average of 24.3 inches. Average maximum temperatures are highest, 80°F., in February and lowest, approximately 40°F., in July.



formerly the southward continuation of the Coorong. Similar sediment also occurs in the southernmost parts of the Coorong itself and is exposed during dry summers when, at the head of this long and narrow inlet of the sea, water-level is lowered by evaporation.

Our investigations were concentrated on the sedimentation in Kingston Lake. Similar sediments have been found between the dune ranges in an area which extends over many hundreds of square miles. Morover, Rogers, Quirk and Norrish (1956) have described dolomite nodules and dolomite-aluminian-sepiolite marl below a surface soil of aluminian-sepiolite, montmorillonite, illite, kaolin, quartz and dolomite from a depression at Tintinara, South Australia, 60 miles NNE of Kingston.

Other examples of plastic dolomitic sediments have been recorded in areas remote from the South-East province. A specimen obtained from Eastern Cove on Kangaroo Island, 140 miles NW of Kingston, has similar composition and properties and seems to have been formed as a shallow water marine sediment. At the base of an evaporite sequence in the bed of Lake Eyre (nearly 600 miles north of Kingston), C. W. Bonython (1956) has recorded beds of dolomite which also contain small amounts of palygorskite, kaolinite, illite, quartz and gypsum. It appears that the occurrence of dolomite in the southeast part of South Australia is not of restricted importance. Direct comparison can be made with beds of similar material formed in comparatively recent times over a very wide area.

COMPOSITION OF THE SEDIMENTS

A typical sample of the dolomitic sediment is white with a grey tinge when dry. Microscopic examination shows an aggregate of particles most of which are so fine that, apart from the fact that they are birefringent, ordinary optical examination gives very little information. Larger particles of sandy and shelly material as well as organic fragments make up varying proportions of each sample. The carbonates are always very fine-grained and were identified by X-ray powder diffraction. Dolomite, even in the surface samples, has the true dolomite structure (space group R3). Dolomite is always accompanied by calcite but calcite may occur without dolomite. Some X-ray powder diffraction lines are very broad. Intensity profiles of these lines are highly asymmetric and work is proceeding on them. The unit cell of the calcite is generally smaller than that of pure calcite, suggesting solid solution of magnesium in the calcite. The dolomite generally has a slightly larger unit cell than pure dolomite. Further X-ray analyses are in progress.

Six samples collected from widely spaced localities and at various depths were selected to illustrate the general mineral and chemical composition of the carbonate-bearing sediments. Compositions are given in table 1 and localities in figure 1. Samples A. 78.1, A. 78.17, D 41 and USE 7-4 can be described as white, extremely fine-grained carbonates cementing quartz grains and organic fragments. D 45 and W 6-4 are dark-gray quartz sands with discrete carbonate

TABLE 1
Composition of Carbonate Sediments

	A78.1	A78.17	D.41	D.45	USE 7-4	W 6-4
SiO_2						

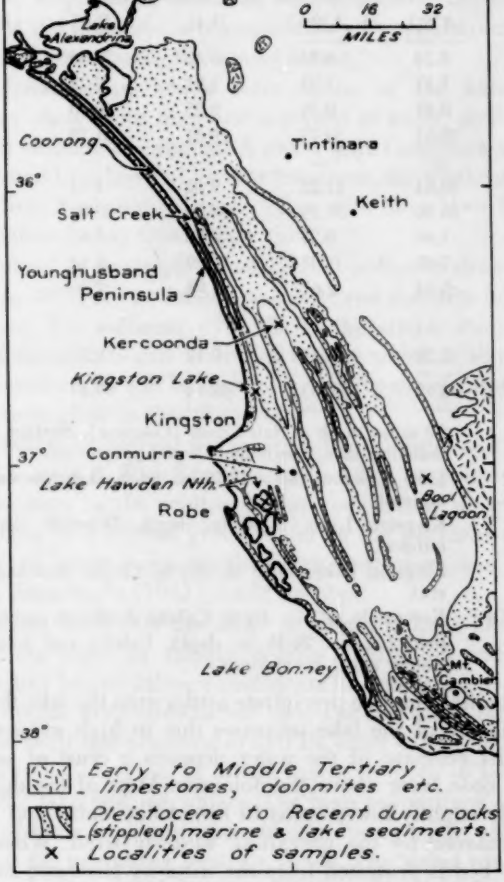


Fig. 1. The South-East of South Australia. Based on S. A. Dept. of Mines geological map, 1953.

grains and many shell fragments. All samples contain minor amounts of clays and halite as well as dolomite and calcite.

Kingston Lake can be taken as typical of many intermittent lakes. Post hole bores put down in this lake and Lake Hawdon North showed 2 to 4 feet of fine carbonate sediment, largely dolomite, above shelly beds and dark sulphur-bearing muds. Fine white sediment occurs on the surface of the Kingston Lake bed at the end of the summer. An annual sedimentation cycle begins when the winter rain accumulates to a depth of 1 to 2 feet in the lake, and plant and animal life begins to reappear in the water. As the weather becomes warmer, water plants growing on the lake floor increase in size and number. It is at this time (November and December) that the lake water may become turbid with fine white sediment which is essentially a mixture of

the bed of the Coorong for several miles at its southern end. The sedimentation sequence must be very similar to that in Kingston Lake. Any salt crystallizing on the surface of the dolomite is removed either by wind erosion or is redis-

	A78.1	A78.17	D.41	D.45	USE 7-4	W 6-4
SiO_2	8.24	6.86	19.42	29.00	17.24	54.34
Al_2O_3	1.11	1.21	1.21	2.28	1.19	13.92
Fe_2O_3	0.81	0.29	0.25	0.40	0.43	4.44
CaO	28.61	34.77	28.61	31.78	30.70	3.11
TiO_2	—	—	—	—	—	0.56
MgO	10.64	11.22	9.42	1.34	10.83	3.75
CO_2	33.26	39.39	32.50	26.05	35.90	6.43
SO_3	1.46	0.27	0.43	0.63	0.02	0.19
NaCl	7.88	1.01	4.29	5.18	0.07	0.48
Total Water	5.64	2.67	1.84	2.26	2.96	12.06
Acid Insoluble Organic Matter as Carbon	1.28	0.34	0.17	0.57	0.42	0.59
	98.93	98.03	98.14	99.49	99.76	99.87

SAMPLE A78.1 — 10 miles south of Salt Creek (Coorong). Surface layer. Calcite and dolomite in approximately equal proportions.

SAMPLE A78.17 — Lake Hawdon North. 12-18 in. depth. Dolomite dominant carbonate mineral.

SAMPLE D.41 — Kingston Lake. 1½-6 in. depth. Dolomite dominant carbonate mineral.

SAMPLE D.45 — Kingston Lake. 33-36 in. depth. Calcite dominant carbonate mineral.

SAMPLE USE 7-4 — Kercoonda. 4-7 in. depth. Calcite dominant carbonate mineral.

SAMPLE W 6-4 — Bool Lagoon. 24-36 in. depth. Calcite and dolomite in approximately equal proportions.

calcite and dolomite. The fine precipitate settles onto the lake floor. During the summer the salinity of the lake increases due to high evaporation and low rainfall. The last remnant of the water deposits a crust of salt which, as it dries, forms a loose layer above the dolomite. Most of the dolomite-forming lakes are merely slightly lower areas in broad flat plains and from these the salt layer is removed by the prevailing westerly wind. Where, much more rarely, the lake bed is protected from the wind by trees and sandhills the salt accumulates. In lakes where dolomitic sediment has been forming for very many years the proportion of salt in the consolidated sediment is quite minor even though, as we will see, sodium and chlorine are overwhelmingly the most abundant constituents of the water in the present lakes.

A very similar cycle must prevail in the shallow sea waters at the head of the Coorong. Water level in the Coorong must be mainly controlled by two factors—first, the seasonal rise during the wet winter and the corresponding fall due to evaporation in the summer, and secondly, by the amount of water flowing out of the River Murray. A large volume of water flowing from the Murray mouth will bank up water at the open end of the Coorong and keep the level high. A small flow from the Murray will allow a generally lower level in the Coorong. Variations in these two factors cause differences from year to year but in an average year water-level in the Coorong is high in the winter and low in the summer. In a normal summer, lowering of water-level exposes

TABLE 2

Saline Content of Water Samples

on the surface of the dolomite is removed either by wind erosion or is redissolved as the water rises during the winter season.

The interdunal areas, which seem to be of the nature of former "Coorongs", may show more than one sequence of muds, shelly beds and the fine precipitated carbonate sediment. A drain near Conmurra shows two such sequences separated by a layer of kunkar limestone, the whole section having a thickness of 8 feet. Such sedimentary cycles must have been frequent in the South-East province during Quaternary time.

Partial analysis of a sample of suspended sediment shows: CaO, 39%; MgO, 31%; CO_2, 30%. X-ray data show calcite and dolomite in approximately equal proportions. The sediment (SW 15) in the sample studied was present to the extent of about 0.05 gms in 100 ml of lake water or about 2 percent of the total saline content. As will be seen later the amount of suspended sediment varies from place to place in the lake water.

The composition of natural waters from the Coorong and from Kingston Lake is given in table 2. The Kingston Lake water is typical of water from many similar sources in the southeast. For comparison we give analyses of what can be taken as a typical groundwater in the province (Drain L) and two analyses of sea water, one from the South Australian coast near Adelaide, the other being Sverdrup's (1942) world average.

These analyses show that the water in Kingston Lake has essentially the composition of sea water in various degrees of dilution and concentration. The Coorong water has its saline constituents in similar proportions. Drain L and tributary drains were constructed to lower the water table over a very wide area in the southeast province so that its water can be taken as typical of the groundwater of the region. It differs markedly both in salinity and composition from the lake and sea waters. The high proportions of Na and Cl in all the waters of the region are undoubtedly due to cyclic salt blown inland from the sea by the prevailing westerly winds. The water which accumulates to form lakes in the interdunal flats is rainwater which has dissolved the cyclic salt dust either in the air or distributed over the land. It is from such water, which in composition is essentially diluted or concentrated sea-water, that dolomite precipitates in Kingston Lake, e.g. analysis 5, table 2.

ORIGIN OF THE SEDIMENTS

Microscopic examination of the suspended sediment (sample SW15) referred to above does not show the presence of any structures which would indicate that the sediment had been formed by an organism, although a small proportion of faecal aggregates suggest ingestion by small crustacea. Electron micrographs of this sediment have been made by Mr. J. Farrant of the Chemical Physics Section, C. S. I. R. O. Division of Industrial Chemistry. These showed the presence of well formed rhombohedra of up to 20 microns cross section, but there was no morphological evidence of organic origin.

Although the associations described in this paper may have wide implications, the limited nature of the results so far achieved is freely admitted by the

Saline Content of Water Samples

	Coorong 3½m. S.E. Salt Ck.			Kingston Lake			Sea Near Adelaide	Sver-drup	Drain L Near Robe		
Month	June	Nov.	Jan.	June	Nov.	Jan.			June	Nov.	Jan.
No.	1	2	3	4	5	6	7	8	9	10	11
Cl	55.9	55.8	55.8	56.0	55.9	55.3	55.5	55.04	48.5	49.9	50.1
SO_4	7.5	7.6	7.6	6.3	6.2	7.5	7.9	7.68	9.5	8.7	9.6
CO_3	0.1	0.2	0.1	0.3	0.5	0.1	0.2	0.41	6.1	5.2	4.8
Na	31.8	31.9	31.7	34.3	34.1	34.2	32.2	30.61	27.3	29.0	28.3
Ca	1.0	0.9	1.0	0.8	0.6	0.4	1.1	1.15	4.0	2.8	1.3
Mg	3.7	3.6	3.7	2.3	2.5	2.6	3.8	3.69	4.6	4.4	5.8
% Salinity	7.05	4.7	5.4	3.33	2.44	22.6	3.8	3.5	0.27	0.25	0.28

Our observations have shown that carbonate precipitation can take place in waters which have only half the salinity of average sea water. Precipitation of carbonates in such solutions could be brought about by a rise in pH. The presence of vigorous plant life in water can have a very considerable effect on the pH of the solution. Baas-Becking (1934) has shown that the extraction of carbon dioxide from lake water by plants during photosynthesis can raise the pH to 9.3 in strong sunlight. The pH may fall to below 8 at night as the water absorbs CO_2 from the air.

That there is a close relation between plant growth, rise in pH, and precipitation of dolomitic sediment in Kingston Lake seems certain. Much work still remains to be done before more complete details of the processes are known. More or less continuous records of pH changes and correlation with precipitation and such factors as sunlight, temperature and salinity appear to be necessary. However, our observations to date have shown that precipitation of dolomitic sediment takes place during the spring and early summer when plant growth is in its most vigorous phase. It has also been observed that during sedimentation the water is most turbid, i.e. the precipitate is most plentiful, where plant masses are most plentiful. Such water has shown a pH of 9.2, although it has not yet been possible to determine pH maxima. The normal figure for these waters in equilibrium with air is 8.2-8.4. It has been mentioned earlier that the most common plant in the lakes and obviously the one most responsible for pH changes is *Ruppia maritima* Linn., although sedges and small algae are also present.

The association described here of shallow saline water, plant growth, elevated pH and dolomitic sedimentation has undoubtedly, we believe, been effective in an otherwise insignificant salt lake near Kingston. We see no reason to believe that this association is not of widespread occurrence. We know that dolomitic sediments of this nature have been formed over hundreds of square miles in the southeast province. We know that identical sediments are forming in sea water in the Coorong today. Admittedly the Coorong is an unusually attenuated gulf but similar conditions could presumably develop in many places where areas of shallow sea water are relatively undisturbed and the climate is suitable for vigorous plant growth.

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POLYMETAMORPHIC ROCKS OF BLUE RIDGE FRONT NEAR OLD FORT, NORTH CAROLINA*

Although the associations described in this paper may have wide implications, the limited nature of the results so far achieved is freely admitted by the authors. Much more detailed continuous observations are necessary at Kingston Lake which however provides an excellent subject as it has some of the characters of a "closed system" with a well-defined annual cycle. A study of the sediments and sedimentary processes in the Coorong is also necessary and could keep many investigators employed for a long time. However, it could easily supply information of the utmost importance. We still do not know the precise conditions under which dolomite forms in such precipitates in preference to one of the forms of calcium carbonate. Perhaps these dolomitic sediments will provide a solution to this problem.

ACKNOWLEDGMENTS

Our thanks are due to Dr. B. J. Skinner, Professor J. G. Wood, Dr. H. B. S. Womersley, Professor E. A. Rudd and Sir Douglas Mawson for their interest and help both in field and laboratory; to the Director and the Chief Analyst of the South Australian Department of Mines (Mr. T. R. Frost) for analyses of water samples and sediments; Mr. John Hutton, C.S.I.R.O. Division of Soils for anlysis of suspended sediment; Mr. J. Farrant, C.S.I.R.O. Division of Industrial Chemistry for making electron micrographs; and to Dr. B. G. Forbes who collaborated in the early stages of this investigation.

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A reconnaissance geologic map of the area was made by Keith (1905), who showed a terrane of "Archean" granite and gneiss with lenticular inter-

POLYMETAMORPHIC ROCKS OF BLUE RIDGE FRONT NEAR OLD FORT, NORTH CAROLINA*

WARREN B. HAMILTON

ABSTRACT. The five miles of spectacular new highway cuts between Smiths Gap and Old Fort, North Carolina, expose polymetamorphic rocks. Precambrian(?) gneisses and allied rocks, and possibly also tectonically intercalated upper Precambrian(?) metasedimentary rocks, were pervasively sheared and slightly recrystallized and reconstituted, probably during early Paleozoic time. The resultant rocks are cataclasites, of which flaser gneisses are most abundant, and mostly have mineral assemblages of the biotite-chlorite subfacies. The cataclastic foliation is generally parallel to layering of the plutonic rocks, and has a general southeast dip. The cataclastic lineations are nearly parallel to the strike of the foliation, and are parallel to the axes of late folds.

INTRODUCTION

Three million cubic yards of earth and rock were excavated for the 5 miles of the new route of U. S. Highway 70 down the Blue Ridge front between Smiths Gap and Old Fort, North Carolina, and the resulting road cuts are among the highest and most continuous in the Southeast. This note is based on a brief study of those cuts, and the examination of 15 thin sections and several times as many hand specimens. The planimetric base map was provided by the North Carolina State Highway and Public Works Commission.

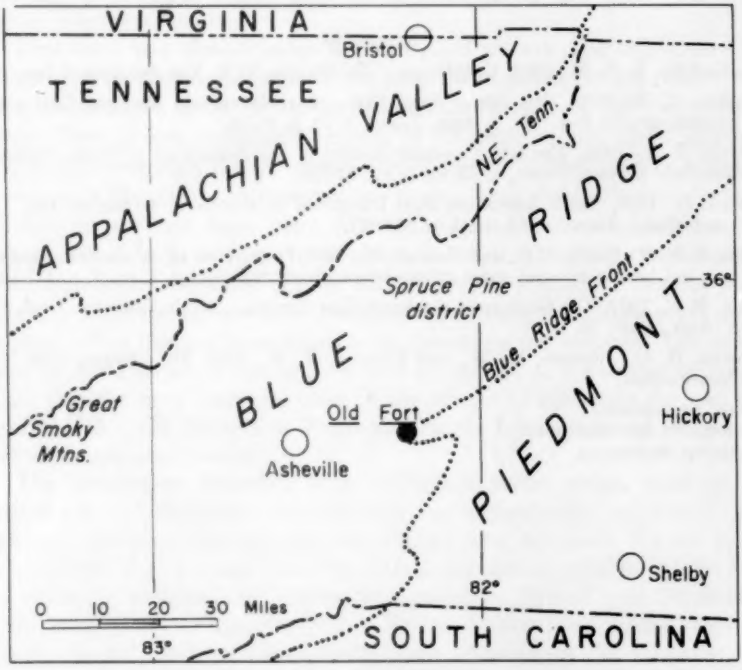

Fig. 1. Index map, showing location of Old Fort area in western North Carolina.

* Publication authorized by the Director, U. S. Geological Survey.

PLATE 1

A reconnaissance geologic map of the area was made by Keith (1905), who showed a terrane of "Archean" granite and gneiss with lenticular intercalations of "Cambrian Brevard schist". These units indicate broad lithologic assemblages, but probably lack the stratigraphic and genetic significance Keith attached to them. The highway crosses the north end of the "Brevard belt", about which much has been written (for summary, see King, 1955, p. 356-358), but little is known.

Fresh rock is exposed in the large road cuts. Many of the small cuts are of saprolite, soft clay-rich residuum in which many structures, both large and small, can be seen almost as well as in fresh rock. The field study was made in early 1954, when the inevitable mantling of fresh rock and slumping and masking of saprolite had scarcely begun.

PETROGRAPHY

All the rocks are polymetamorphic, and strong cataclasis, accompanied by variable low-grade recrystallization and reconstitution, has obscured older textures and mineral assemblages. The rocks are now cataclastic gneisses, with subordinate schists and minor phyllonites. Typically, knots and layers of coarsely crushed white quartz and feldspar lie between darker folia of finely crushed quartz, feldspar, and micas. Quartz and feldspar show much crushing and slight recrystallization; biotite and muscovite show bending, shredding, and slight recrystallization; hornblende shows crushing but no new growth. New minerals include micas, chlorite, epidote-group minerals, and a little garnet. Plagioclase was altered to albite (about An_{10}) with abundant inclusions of muscovite and epidote-group minerals. Photomicrographs are shown in plate 1.

New mineral assemblages belong mostly to the biotite-chlorite subfacies of the greenschist facies, although some belong to the muscovite-chlorite subfacies, and some to the albite-epidote amphibolite facies. The diverse assemblages are intercalated, and no systematic directional progression was noted of either mineralogic grade or of degree of cataclasis.

The dominant rocks are quartz-feldspar flaser and augen gneisses with accessory biotite and muscovite, in layers from a fraction of an inch to a few hundred feet thick. Many layers exposed in large outcrops are lenticular. Textural variants of similar composition include a little mortar gneiss, phyllonite, and blasto-mylonite. Other types include two-mica schist and mica-rich gneiss, amphibolite, and calcite-mica schist. Prior to cataclasis, the rocks belonged at least mostly to a layered plutonic series dominated by granitic gneisses, with less pegmatite, mica gneiss and schist, and amphibolite. Pegmatites are represented by white flaser and mortar gneisses, strewn sparsely with green muscovite. Textures and mineralogy of some rocks suggest that they might have been middle-grade meta-arkoses and schists prior to cataclasis; but so complete has been the obliteration of pre-cataclastic textures in the specimens examined that this possibility cannot be verified by so brief a study. These latter rocks do not correspond to Keith's Brevard schist, a term which apparently was applied to any thick intercalations of schistose rocks.

STRUCTURE

A. Photomicrograph of flaser gneiss, showing large muscovite grain bent into V. Light laminae are of granular quartz and feldspar; dark laminae include shredded mica. Plane light.

B. Photomicrograph of sheared two-mica gneiss (lower left) and flaser gneiss (upper right), showing bent and shredded micas. Plane light.

C. Boudin of amphibolite enclosed in flaser gneiss. Plutonic foliation of amphibolite is parallel to the 6-inch scale, and is truncated against the cataclastic foliation of the flaser gneiss. Smaller boudins of dark rocks lie above the large boudin.

reports on these areas are in preparation. Another study is under way by R.

The pronounced cataclastic foliation is almost everywhere parallel to the older compositional layering of the plutonic rocks. Foliation and layering have a general low to moderate southeast dip, complicated by wrinkles and small folds with nearly horizontal axes and southeast-dipping axial planes (fig. 2).

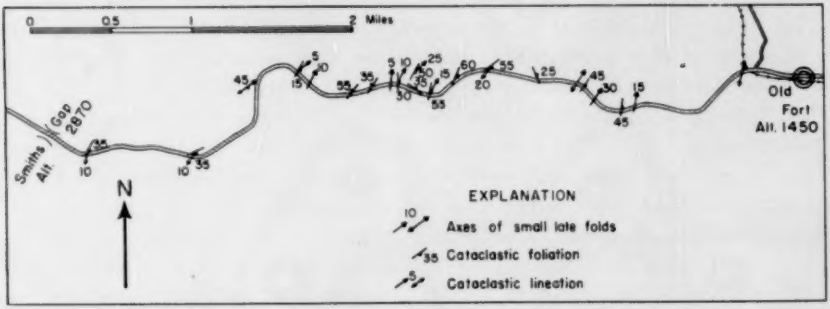

Fig. 2. Map showing geologic structures along U. S. Highway 70 between Smiths Gap and Old Fort, North Carolina.

The cataclastic foliation cuts pegmatites that are oblique to the layering of the rocks. Marked linear structures lie within the cataclastic folia: augen, mica trains and elongate grains, and boudins, with mica trains the most conspicuous. These structures are parallel to each other and lie near the strike of the foliation, plunging gently either northeastward or southwestward. This parallelism of mica trains (generally *a*-tectonites) and boudins (generally *b*-tectonites) is an unusual feature for cataclasites, and, considered with the parallelism of the linear structures to the regional strike of the rocks, suggests that the linear structures formed perpendicular to the direction of tectonic transport. If the folds of the foliation were formed late in the same episode of shearing, rather than in a subsequent episode of deformation, then this suggestion would be confirmed, as the fold axes are essentially parallel to the cataclastic lineations.

Many contacts between rock types are shear surfaces. This is shown strikingly where amphibolite is involved; amphibolite was apparently far more resistant to internal shearing than was quartz-feldspar-mica gneiss, and was cut into boudins around which flowed smoothly the cataclastic foliation of the flaser gneisses (pl. 1, C).

REGIONAL RELATIONSHIPS

That polymetamorphic rocks are widespread in the Blue Ridge was early recognized by Keith, who mentioned the pervasive shearing of gneissic and granitic rocks in many of his folios, including that covering this area (1905). King (1955, p. 341) overlooked this critical point in Keith's interpretation. Jonas (1932) noted retrograded rocks over wide areas.

Polymetamorphic Precambrian basement rocks have been studied in detail in the Great Smoky Mountains by J. B. Hadley and Richard Goldsmith, and in northeast Tennessee and adjacent North Carolina by the writer, and

Jonas, A. I., 1932, Structure of the metamorphic belt of the Southern Appalachians: Am.

reports on these areas are in preparation. Another study is under way by B. H. Bryant, between the Spruce Pine and northeast Tennessee areas. These studies show that the basement rocks were metamorphosed, along with younger rocks such as those of the Ocoee series, at variable grade. Over broad areas, this re-metamorphism of the basement rocks was at low grade, thus retrogressive; over other areas, it was at high grade. Probably most of the rocks of the Blue Ridge were affected, although much more study will be needed before this is known, How much of the retrogression is the product of a single episode of metamorphism can similarly only be inferred at present.

Although Jones (1932) hypothesized great regional overthrusts along belts of retrograded rocks in the southern Appalachians, she did not recognize that in the Blue Ridge, and probably also in the inner Piedmont, the intervening high-grade rocks were also polymetamorphic; her "overthrusts" are apparently instead zones of relatively lower grade metamorphism.

The retrograde metamorphism of the rocks near Old Fort is presumably correlative with that near Spruce Pine, 20 miles away and nearly on-strike. At Spruce Pine, flaser gneisses and other cataclasites are widespread, but unfortunately were little studied by geologists working there. (Thus Eckelmann and Kulp, 1956, p. 297, note that the great majority of gneisses studied are cataclastic, but overlook the complexities such shearing produced; and Kulp and Poldervaart, 1956, make no mention of this pervasive shearing in a paper entitled "The metamorphic history of the Spruce Pine district".) The retrogression is probably older than the pegmatites of the Spruce Pine district. Many radioactive-element dates indicate an age of about 340 million years for the pegmatites (Kulp and Poldervaart, 1956, p. 400). The information available on the pegmatites does not suggest them to be much crushed, although their wall rocks are widely granulated (D. A. Brobst, personal communication). The definitive study to prove the relative ages of pegmatites and retrogression has yet to be done, however.

The best data available thus date the retrogression as younger than the deposition of the upper Precambrian(?) Ocoee series of the Great Smoky Mountains, and older than the probably Ordovician or Silurian pegmatites at Spruce Pine. It is reasonable to suggest that the retrogression was part of a cycle of regional metamorphism which ended in this part of the Blue Ridge with the emplacement of the Spruce Pine pegmatites.

Most of the Blue Ridge Front rocks near Old Fort are similar to rocks of the plutonic basement beneath the upper Precambrian(?) Ocoee series of the Great Smoky Mountains. A few intercalations of Ocoee or younger rocks might be present near Old Fort, but if present such intercalations must be tectonic. Such possible intercalations might be part of the Brevard belt, but the rocks mapped as Brevard schist in this area by Keith appear to be mostly polymetamorphic schists derived from the plutonic rocks.

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A RE-DETERMINATION OF EQUILIBRIA IN THE SYSTEM $MgO—H_2O$ AND COMMENTS ON EARLIER WORK*

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ABSTRACT. The univariant p-t curve along which brucite, periclase and water coexist has been re-investigated using static methods and new quenching techniques. The new curve is found to lie essentially within the experimental error limits of the curve previously determined in this laboratory and approximately 50°C higher than values obtained by calculation or certain semi-dynamic experimental methods. The results may be used to correct the total ΔF value for the reaction $Mg(OH)_2 \rightleftarrows MgO + H_2O$ at various pressures and temperatures.

Some comments are made regarding earlier papers dealing with the calculation of p-t curves from thermochemical data.

INTRODUCTION

The reaction $Mg(OH)_2 \rightleftarrows MgO + H_2O$ was used by Giauque and Archibald in 1937 in one of the important determinations of the entropy of water. A few years later Giauque used the same reaction to illustrate important differences to be expected if one uses thermochemical parameters determined on phases which are not identical with those actually involved in a phase equilibrium investigation. A difference of about 10 percent in the heat content of very finely divided periclase from that of the well-crystallized material was found. This fact had itself been known for a long time (Taylor and Wells, 1938).

Bowen and Tuttle (1949) in the first recorded study of a system of petrologic interest which had water as one component presented data on the system $MgO—SiO_2—H_2O$. They presented a p-t curve for the reaction $Mg(OH)_2 \rightleftarrows MgO + H_2O$ which passed through points at 885°C and 6,000 psi and 895°C and 15,000 psi. Roy, Roy and Osborn (1953) (see also Roy and Roy, 1955) in their study of the system $MgO—Al_2O_3—SiO_2—H_2O$ found evidence from ternary equilibria which contradicted the brucite-periclase curve of Bowen and Tuttle. A curve was therefore determined with some pains but little precision (Roy, Roy and Osborn, 1953) and it was shown that Bowen and Tuttle's data could be explained by the failure to "quench" the reaction satisfactorily. The difficulty though recognized persisted in our study and the data had therefore to be "interpreted" somewhat more than is usually necessary.

In 1955 MacDonald calculated free energy values for water at elevated temperatures and pressures from Kennedy's (1950) p-v-t data. He illustrated the use of these data in petrological problems by using them in (presumably) a rather elaborate calculation of p-t equilibria in the system $MgO—H_2O$. Presuming that all previous authors had set correct error limits on their data, MacDonald estimated an error limit for his calculated p-t curves of ±50°C. (In fact, MacDonald presented two p-t curves depending on the state of subdivision of the phases, and more will be said regarding this in a later section.) It was found that Roy, Roy and Osborn's experimental curve lay just within

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enormously from system to system, some clay and calcium-silicate-hydrates

the error limit of MacDonald's upper curve representing the decomposition of well-crystallized brucite to "fine" periclase. After the appearance of MacDonald's paper we made a few runs to check our earlier curve and found it relatively satisfactory.

Together with Professor O. F. Tuttle attempts were also made to use dynamic methods of slow DTA patterns[1] under water pressure and also a p-t plot in a closed system with brucite and water. Neither of these methods proved as satisfactory as the static method. Kennedy (1956) simultaneously reported the successful use of a p-t plot method in the study of the same reaction. He used a very large sample (200 gms compared to our 2 gms) and the pressure change caused by release or absorption of water by the solids was therefore more marked. The curve presented by Kennedy lies about 50°C lower than our own, almost coincident with one of MacDonald's calculated curves. Another, more round-about calculation of the equilibrium has been carried out by Weeks (1956) who arrives at temperatures about 10°C below the upper curve of MacDonald.

In 1956 Majumdar and Roy attempted to evaluate the usefulness of various methods of calculating p-t equilibria from *presently available* thermochemical data. They demonstrated the relatively high accuracy demanded of the heat of formation and Cp values if the curves were to be even approximately correct. A simplified calculation gave a brucite dissociation curve essentially identical with MacDonald's. It was recommended that one or two experimental points could be used to provide an empirical correction to such calculated curves at moderate pressures, and then the calculated curves could serve as more reliable extrapolations, especially to lower pressures.

Since it appeared unlikely that as reliable thermochemical data as are available for this system will soon become available for any other simple, petrologically significant system, and since Kennedy's data conflicted with our own, we considered it worthwhile to re-determine the p-t curve for the reaction $Mg(OH)_2 \rightleftarrows MgO + H_2O$. The previous determination was one of our earliest efforts and since then our equipment and techniques have been improved in several ways.

EXPERIMENTAL

Although the pressure DTA apparatus developed here was able to handle pressures up to 3000 atmospheres it was decided to use a static method since the actual phases involved in the equilibrium could (probably) be examined. The innovation used here, devised in a study of the hydration of the rare earth oxides (Shafer and Roy, 1955), is a so-called leak-quench or 'p-t' quench. As the name implies it entails the sudden release of pressure (in a fraction of a second) by breaking the seal at the top of the 'test-tube' or 'cold-seal' pressure vessel, followed by quenching the bomb in cold water. In each system one can determine by trial and error the length of time a hydrate can be heated 'dry' at a certain temperature, without decomposing appreciably. This varies

[1] These differential thermal analyses were performed in a ¼ in. i.d. test-tube bomb using a very simple adapter for packing in thermocouples. Heating rates were one to two degrees centigrade per minute. The method was unsuccessful due to the very rapid corrosion of the thermocouples and the non-reversibility of the heat effect.

enormously from system to system, some clay and calcium-silicate-hydrates withstanding several hours, while some hydrates such as $Ca(OH)_2$ can only be heated for a minute or two. Once a safe interval between the p-quench and t-quench has been determined, it can be used within a reasonably wide p-t range. In the brucite case it was found that the interval had to be as short as possible.

The experimental procedure involved was therefore as follows; these starting materials were used:

1. C.P. MgO heated at 1400°C.
2. Brucite (well-crystallized) from Texas, Lancaster County, Pennsylvania (Genth Mineral Collection, No. 262.13).
3. Precipitated C.P. $Mg(OH)_2$

Each of these is placed in a separate gold or platinum container and the three placed side by side in a cold-seal vessel. Temperatures are read in a thermocouple well directly opposite the samples, with only about 1/4 inch of metal separating them. The vessels are heated in large heat capacity furnaces with a fairly long 1 to 1 1/2 inch even temperature (±5°C) zone. The temperature of a thermocouple placed in the position of the samples and 'packed out' of the standard pressure vessel, was read at 5000, 10,000 and 15,000 psi and compared with the temperature read in the usual thermocouple well. No difference (±1°C) could be recorded on the automatic potentiometric recorder over a several-hour period. The existence of violent convection currents is also apparently ruled out by this. Temperatures were read on a Honeywell Precision Automatic Indicator, and recorded on a Honeywell Multipoint Recorder. While neither of these instruments was calibrated specifically for any run, they are cross-checked several times a day against a L & N Portable Precision Potentiometer and are always checked against each other. The chromel-alumel couples were not calibrated specifically for the job since they were changed so frequently. However, they were made from calibrated wire and together with frequent changing (i.e. 3-4 days at, say 650°C) this should not be an appreciable factor in the totalization of errors. Pressure measurement was less precise. Gauges of different ranges were used and it was not possible to calibrate our 0-80,000 psi gauges directly since the limit of the dead weight tester available is 20,000 psi. A 0-50,000 psi gauge was calibrated by direct comparison with a 16 inch 0-20,000 Heise gauge used as a secondary standard. The 0-50,000 gauge was then compared with a 0-80,000 gauge, up to 40,000 psi. Unfortunately above 20,000 psi the comparison of the gauges led to a change from a negative correction of about 500 to a positive one of +1000 psi. Up to 20,000 psi therefore pressures are accurate to 0.5 percent although they cannot usually be read to better than 1 or 2 percent without special effort. Between 20 and 30,000 psi, the 50,000 psi gauge was presumed to be correct (there being no correction at 20,000 psi), and at 40,000 psi and above, the 80,000 psi gauge reading had to be used. A pressure value is unlikely to be more accurate than ± 2 percent and furthermore there is no record of the pressure although it is presumed to have been constant if the temperature did not vary and there was no consistent leak. An estimate of the precision of the points is therefore ±3°C and ±2 percent in pressure. The

temperature could not be this good if it were not for the fact that only relatively short runs were involved. In *all* the runs the petrographic microscope and powder x-ray patterns were used for identification.

RESULTS

The following arguments are used to determine what phases are stable under the conditions of any given run. Both p-t quench and the usual t-quench runs were made.

I.—If in a p-t quenched run of the usual length all the samples yielded well-crystallized brucite the point MUST be in the brucite field. For, granting the possible hydration of the original periclase during the heating up period, all three samples would have dehydrated completely in say half-an-hour if the conditions were in the periclase field. Since all water was removed, before quenching, the presence of large brucite crystals (often 1 mm across) must be taken as *unequivocal* proof that the p-t conditions lie in the brucite field. Runs 210 and 207 were of this type. They, alone, appear to establish that the curve by Kennedy is in error.

II.—In a temperature-quenched (t-quench) run if all these samples show under the petrographic microscope well-formed octahedra of periclase (e.g. runs 271, 306) we must similarly conclude that the conditions are in the periclase field. Since in the heating-up period only the periclase can be converted to brucite and not vice versa, the formation of periclase especially in large crystals must have occurred under the p-t conditions of the run. Moreover, their survival through a temperature-only quench is a reflection of their "superior" crystallinity.

III.—A less simple, but nevertheless clear-cut case is that obtained in a p-t quench when all the samples (which in nearly all cases gave the same products) show microscopically mottled or 'corroded' brucite crystals (e.g. runs 283, 284, and 285). The X-ray pattern of such material is neither that of a well-crystallized brucite nor periclase but shows almost no Bragg reflections at all, except for very broad peaks of periclase or less frequently brucite. There is no subjectivism involved in this judgment as can be seen in figure 1. These runs are also identified as points in the brucite field since, it is reasoned, if periclase were stable and had been formed it could not have disappeared during a mere cooling-down process in the absence of water.

IV.—Conversely in certain t-quench runs the formation of very poorly crystallized brucite, sometimes associated with the appearance of a few large periclase crystals which survived, is regarded as evidence for a point in the periclase field (e.g. runs 22, 23 and 24). If brucite were stable and had formed, it could not have dehydrated during the cooling with water present. (The 'p-t curve' of a vessel on cooling always lies well inside the brucite field.)

Using these criteria the curve drawn in figure 2 is obtained as our evaluation of the univariant equilibrium between brucite and periclase plus water vapor. The symbols are explained in the legend. It will be seen that by a curious coincidence none of the points from our earlier paper is actually incorrect. In the earlier paper extrapolation above 15,000 psi had curved in the line too sharply, as revealed by the newer runs at high pressures. The curve

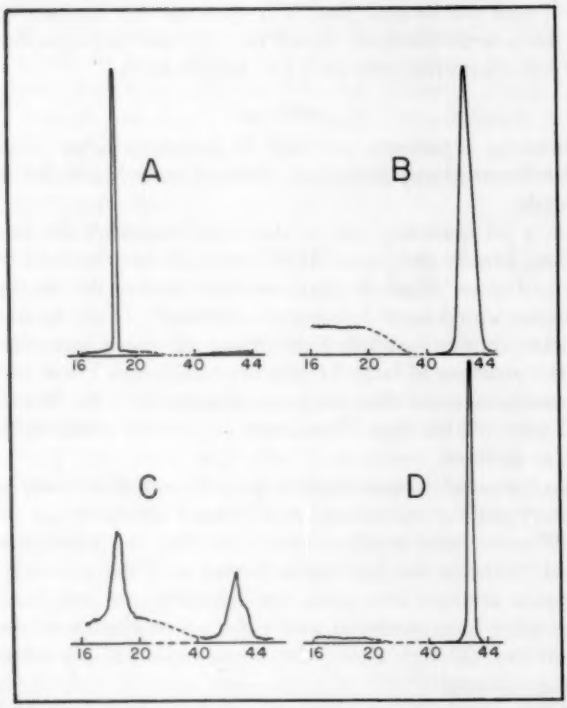

Fig. 1. Partial x-ray diffractometer patterns of quenched samples, CuKα radiation. A. Well crystallized brucite, t-quench; B. Poorly crystallized periclase formed from $Mg(OH)_2$ heated dry 5 minutes at 680° = MgO*; C. Brucite remnant, periclase beginning to form on p-t quench of brucite; D. Sample B heated at 680°C, 15,000 psi for 3 hours, p-t quenched, demonstrating rapid conversion of MgO* to well-crystallized MgO.

now appears to pass through points at 642°C and 15,000 psi, 667°C and 30,000 psi and 705°C at 60,000 psi (last point less accurate).

These results place the new curve some 40-50°C above the calculated curves and the experimental curve of Kennedy. The discrepancy between Kennedy's results and ours needs to be explained. The only observation which may be relevant concerns the temperature measurements in Kennedy's vessel. In a metal vessel of such a large capacity, unless a furnace three or four feet in length is used, the temperature gradients within the bomb must be severe. The temperatures were measured in the center of the charge and it appears possible that the outer parts of the charge could have been at a definitely higher temperature. Moreover, the stepwise reactions noted by Kennedy and explained by recourse to presumed variations in particle size may in reality be due to the thermal gradient within the sample.

THE QUESTION OF "FINE-GRAINED PERICLASE"

In a paper not frequently referred to, Giauque (1949) has dealt in detail with the importance of the nature of the reactants and products in p-t equili-

TABLE I

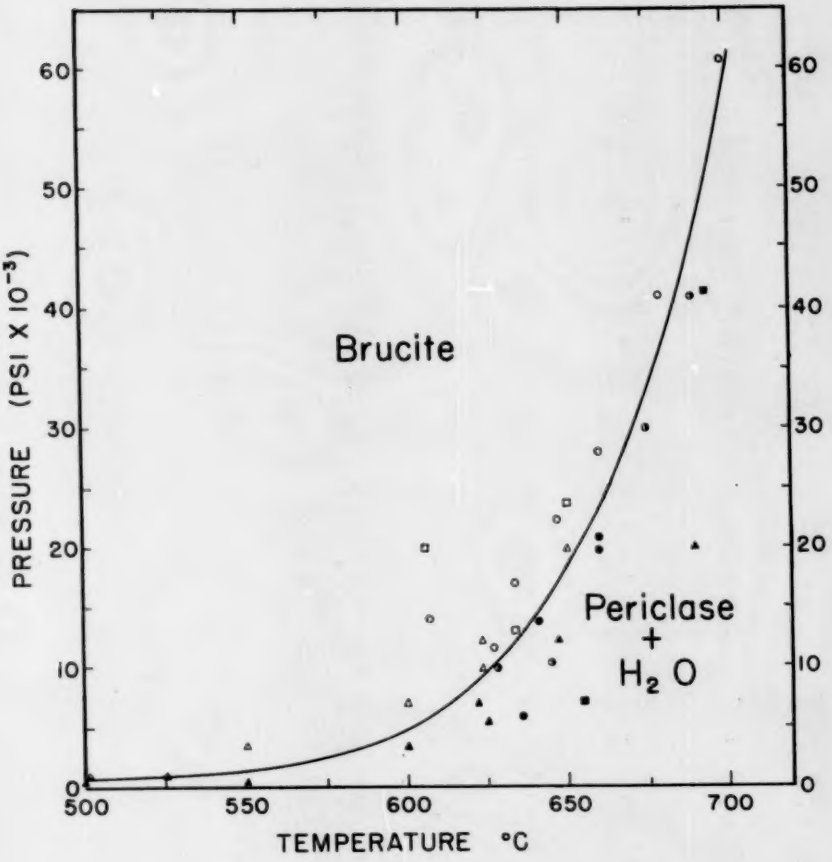

Fig. 2. P-T curve for the reaction brucite = periclase + H_2O.

Symbols
△ Brucite
▲ Periclase (+ brucite formed on quench.)
} Data from Roy, Roy and Osborn (1953) t-quench

○ Brucite
◑ Periclase (Mixed with brucite formed on quench.)
● Periclase (Large crystals, little or no attack.)
} t-quench

□ Brucite (or decomposed brucite, dehydrated on quench)
■ Periclase
} p-t quench

} Data from Table I.

TABLE I (Continued)

TABLE I

Hydrothermal Quenching Data for Brucite-Periclase Equilibrium*

Run No.	Temp. (°C)	Press. (psi)	Time (hrs)	Quench Type	Starting Material	Phases Present
221	603	20,000	24	p-t	Bru	Poor per; decomp bru
53	607	14,300	48	t	Bru	Bru
54	"	"	"	t	$Mg(OH)_2$	Bru
55	"	"	"	t	MgO	Bru
207	"	20,000	24	p-t	Bru	Decomp bru
208	"	"	"	"	$Mg(OH)_2$	" "
209	"	"	"	"	MgO	" " , poor per
52	627	11,300	48	t	MgO	Bru
4	628	10,000	72	t	Bru	Per + l. bru
5	"	"	"	"	$Mg(OH)_2$	Bru + per
6	"	"	"	"	MgO	Bru
210	634	13,000	120	p-t	Bru	Decomp bru (l. bru)
211	"	"	"	"	$Mg(OH)_2$	" " (l. MgO)
56	"	17,000	48	t	Bru	Bru (large xls)
57	"	"	"	"	$Mg(OH)_2$	Bru
58	"	"	"	"	MgO	Bru
306	637	5,500	168	t	Bru	Mostly per, small xls
307	"	"	"	"	$Mg(OH)_2$	Per xls
308	"	"	"	"	MgO	Per xls
40	641	13,500	24	t	Bru	Per
41	"	"	"	"	$Mg(OH)_2$	Per
42	"	"	"	"	MgO	Per
1	645	10,300	24	t	Bru	Bru + Per
2	"	"	"	"	$Mg(OH)_2$	Per + Bru
3	"	"	"	"	MgO	Per + Bru
280	647	22,200	24	t	Bru	Bru
281	"	"	"	"	$Mg(OH)_2$	Bru
282	"	"	"	"	MgO	Bru
283	650	23,700	24	p-t	Bru	Decomp bru
284	"	"	"	"	$Mg(OH)_2$	" "
285	"	"	"	"	MgO	" "
43	655	7,500	24	p-t	Bru	Per
44	"	"	"	"	$Mg(OH)_2$	Per
45	"	"	"	"	MgO	Per
286	660	19,800	48	p-t	Bru	Small per xls
287	"	"	"	"	$Mg(OH)_2$	Large per xls
288	"	"	"	"	MgO	" " "
271	"	20,700	72	t	Bru	" " "
272	"	"	"	"	$Mg(OH)_2$	" " "
273	"	"	"	"	MgO	" " " l. bru?
13	661	27,800	24	t	Bru	Bru large xls
14	"	"	"	"	$Mg(OH)_2$	Bru
15	"	"	"	"	MgO	Bru
25	676	30,000	48	t	Bru	Per large xls + bru
26	"	"	"	"	$Mg(OH)_2$	" " " " "
27	"	"	"	"	MgO	Bru(diffuse) + large Per xls
16	679	41,200	24	t	Bru	Bru large xls
17	"	"	"	"	$Mg(OH)_2$	" " "
18	"	"	"	"	MgO	Bru

TABLE I (Continued)

22	689	41,200	96	t	Bru	Per large xls + l. bru
23	"	"	"	"	$Mg(OH)_2$	" " " " bru
24	"	"	"	"	MgO	Bru + large per xls
28	694	41,500	24	Mixed	Bru	Per + v.l. bru
29	"	"	"	"	$Mg(OH)_2$	" " l. bru
30	"	"	"	"	MgO	" " " "
37	700	61,000	2	t	Bru	Bru large flakes
38	"	"	"	"	$Mg(OH)_2$	Bru
39	"	"	"	"	MgO	Bru smaller flakes

* Abbreviations = Bru: brucite, Per: periclase, decomp: decomposed, l.: little, v.l.: very little, xls: crystals.

brium studies when these are correlated with thermochemical measurements. It is contended that frequently at low pressures and temperatures a product may be obtained which is much higher in heat content than the same phase prepared in large crystals. Experimental evidence for this is quite strong in the case of MgO itself; but it should be remarked here that MgO is one of the best examples which can be cited. The nature of this phase of greater heat content in lower-temperature dehydrated brucite has been studied by Buessem (1936). It should be made clear that the higher free energy and heat content of this MgO is not due exclusively to particle size. Buessem has demonstrated the strain in the lattice due to the inheritance of the brucite atomic positions. Particle size reduction alone cannot increase heat content in the required amount and the statements in Kennedy's paper which imply this should be corrected in part.

For the purpose of this discussion we shall refer to the 'strained MgO' as MgO*, an active or higher free energy form of MgO. It is known that in actually measured cases H_{MgO^*}[2] is 10 percent greater than H_{MgO} and of course the corresponding free energy term for MgO* is substantially higher than for MgO.

The important point to be made is that in any consideration of stable equilibrium, MgO* must be regarded merely as a metastable polymorph of MgO. Thus, for a consideration of stable equilibrium in the system $Mg(OH)_2 \rightleftarrows MgO + H_2O$ it is quite irrelevant to introduce considerations involving MgO*. One may, of course, consider metastable equilibria between MgO* and water. However, if this is to be meaningful it must first be established that MgO* can exist under the conditions being discussed. There is no doubt that MgO* can be prepared (indeed different MgO* products of varying degrees of metastability and excess free energy can be made and maintained up to even relatively high temperatures (1000°C or more) *under low partial pressures* of water. In geological time and especially under geological conditions can MgO* persist? Does MgO* persist in a bomb near the p-t curve? It is suggested here that it cannot do so in the laboratory and therefore it is meaningless to propose that it does in nature. Kennedy has suggested that MgO* may persist in the p-t region of the univariant curve even for a week. However, we have noted that finely crystallized MgO will convert very rapidly to rela-

[2] Abbreviation for heat content of the phase.

tively large crystals of MgO just above the univariant curve. In fact, at about 2000 atmospheres large well-formed octahedra of periclase will grow from fine periclase in over-night runs. The following experiment confirms this viewpoint: brucite was dehydrated in a bomb at 680°C and a sample extracted. An identical sample was dehydrated at 680°, water pressure at 15,000 psi was admitted for 3 hours, and the sample p-t quenched. The very poorly crystallized periclase of the first sample had been converted to a well-crystallized phase as shown by the broadening of the x-ray diffraction maxima (see fig. 1). In other words MgO* will convert directly to MgO under p-t conditions near the univariant curve even under the conditions used in most hydrothermal work and therefore certainly we do not need to consider it in geological problems. The unfortunate result of these considerations is that it removes the experiment even further from calculation. Among MacDonald's curves for brucite $\rightleftarrows$ MgO + H_2O, the lower curve most nearly applies to the experiment and thus is about 100°C lower than our experimental curve.

It is possible that similar considerations can be applied to brucite as suggested by Taylor and Wells (1938) and that there is a substantially different $Mg(OH)_2$*. There is, however, no clear x-ray or other evidence for a difference of the same magnitude as that between the different 'periclases'. Hence, we cannot justify using MacDonald's upper curve on the basis of the type of brucite. Stated in other words most of the difference in the heats of this reaction obtained on the various combinations of poorly and well crystallized brucite and poorly and well crystallized periclase should probably be attributed to differences in heat content of the various periclases. This maximum difference amounts to about 900-1000 cals/mol.

These arguments are used to show that in our static method we deal with the reaction: essentially stable brucite $\rightleftarrows$ essentially stable periclase + water vapor. It is our belief that the water is a sufficiently good catalyst to convert any MgO* or $Mg(OH)_2$* phases to stabler forms which for all experimental purposes are in their lowest free energy states.

It will be of considerable interest to have our data checked by other laboratories, since if these data are correct one may then proceed to correct the calculated p-t curves along the lines suggested by Majumdar and Roy (1956). Should it transpire that in other well-determined curves involving dehydration the magnitude of the error is similar, it may be possible to correct the free energy values for water in the corresponding pressure and temperature range.

ACKNOWLEDGMENTS

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DESCRIPTION AND OCCURRENCE OF ATOLL PHOSPHATE ROCK IN MICRONESIA*

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ABSTRACT. Beds of phosphate rock on atolls of the northern Marshall islands are related to other phosphate occurrences on low coral islands in other parts of the world. The rock appears to consist of grains of organic limestone cemented by apatite which fills the interstices. The calcium carbonate is replaced partially or in some cases completely by apatite. The occurrence of these beds under surface layers of acid raw humus subjected to a continued accretion of phosphate guano, under trees of *Pisonia grandis*, suggests a genetic relationship. The finely divided calcium phosphate in the guano is thought to be dissolved by the acids of the humus as it is washed down through the humus by rainwater, and then precipitated out on contact with alkaline limestone sediments below. The quantities of this rock available are not thought large enough for modern commercial exploitation but may very well serve to offset local phosphate deficiency in the coconut plantations of the Marshallese people.

INTRODUCTION

During field work in the northern Marshall Islands in 1951 and 1952[1] beds of a brown, usually white-speckled, indurated sedimentary rock were encountered on a number of islands. In texture this is a medium to coarse sandstone, resembling the loose calcareous sediments with which it occurs, but cemented by a brown cement. On analysis it proved to have a variable but high percentage of phosphorus. X-ray analysis showed that apatite is an important component, in certain samples making up almost the entire composition.

This occurrence has been treated elsewhere from the pedological viewpoint (Fosberg, 1954), and a paper is in preparation on its ecological significance. Since such rock is of wide distribution and of geological interest, also, it is appropriate to discuss separately such features of its occurrence and putative history as are of significance to geologists.

This material was first studied with some care on Jemo Island, Marshall Islands, Lat. 10°4′ N., Long. 169°31′ E., and later on several other islands, especially Kwajalein, Ujae, and Bikar, also of the Marshall group.

GEOGRAPHICAL OCCURRENCE

Although individual occurrences are of small extent, usually not more than a few acres, beds of phosphate rock are found on a number of islands in the Marshall group. These include Jemo Island and Kwajalein (Eniwetok Islet), Bikar, Ujae, Wotho, Arno, and Ebon atolls. Fragments of such rock were found on Ailinginae Atoll (Fosberg in 1956). Similar rock is also known from Wake Island (Fosberg, 1954), from Gaferut (W. A. Niering, personal communication) and Kapingamarangi of the Carolines (W. A. Niering, 1956, p. 20, McKee, 1956, p. 19-21) and Onotoa, of the Gilberts (P. E. Cloud, oral communication, 1953). A piece of rock from the uppermost phosphate bed on Kita Daito Jima, collected by D. E. Flint, resembles the beds under discussion in both appearance and mode of occurrence. A few fragments of rock of ap-

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[1] Carried out in connection with surveying operations of 71st Engineer Liaison Detachment, Corps of Engineers, U. S. Army.

parently the character described were found on Malé Atoll, Maldives, by the author in 1956. Malé has been intensively utilized for coconut cultivation for centuries. No native vegetation remains in the locality concerned and no actual beds of consolidated material were seen. Occurrences which, from their descriptions, probably belong here have been reported from Palmyra Island, Washington Island, Fanning Island, Rose Island (G. E. Hutchinson, 1950, p. 183-186, 191-192, and 251), and from Wuwulu, Aua, Manu, and the Purdy Group north of New Guinea (R. C. Hutchinson, 1941). Probably Caroline and Flint Island phosphates are also similar, but information on them is very limited (G. E. Hutchinson, 1950, p. 187). The same is true of the deposits on the Paracel Islands (Clerget, 1932). Some or all of the phosphatic "patinas" and sandstones reported from the coral islands of the western Indian Ocean, Bird, Dennis, Aldabra, St. Pierre, Siren (Cargados Carajos Atoll), Cosmoledo, and others may also belong here (Fryer, 1910a, 1910b, 1911; Gardiner and Cooper, 1910; G. E. Hutchinson, 1950).

STRATIGRAPHIC OCCURRENCE

The normal occurrence of this rock is as a horizontal indurated bed or series of beds lying immediately under a surface layer of peaty raw-humus and immediately over bedded unconsolidated lime sands and gravels of various depths. The thickness of the consolidated material is usually about 5 to 15 cm rarely up to half a meter or more. Thicknesses of up to 2.5 m have been reported, as on Aua Island (R. C. Hutchinson, 1941, p. 239), but it is not certain from the description that the material is exactly comparable to that described here, though it seems very similar. At times, as on Eniwetak Islet, Kwajalein, there are, in addition, nodules of consolidated material embedded in, and lying on the surface of, the humus layer. Fragments may be scattered or piled on the surface where broken by tree-roots or from other causes. Rarely, as on Bikar Islet of Bikar Atoll, two consolidated beds occur. The lower one is covered by sand and gravel presumably deposited there by storm waves or wind, and the upper one lies on this, is much thinner, and is covered by a layer of humus. In some occurrences, as on Ebon Atoll (Hatheway, 1952) Wake Island, Onotoa Atoll, and the western Indian Ocean islands, the humus layer is absent, presumably destroyed during or after clearing of the land for planting or other reasons.

The actual thickness of a particular bed varies locally, that on Jemo, for example, being from about 10 to 45 cm in different test holes and exposures. On Bikar Islet the deposit of sand and debris overlying the phosphate bed tapers in thickness from perhaps a meter at the western side of the islet to zero on the eastern side, and on this an upper, thinner phosphate bed is developed locally.

LITHOLOGY

Lithologically this rock is somewhat variable. It is a medium to coarse sandstone, frequently including larger than sand-size fragments. In texture the cemented fragments are usually like the material of the underlying unconsolidated beds, light-colored grains clearly of organic origin. They may include

foraminiferal tests of different kinds, coral fragments, algal fragments, echinoid spines, and mollusk shells or fragments. All of these are either angular or rounded and worn smooth and usually seem softer than the corresponding uncemented particles. Their outer layers may be softened and brown. The matrix or cement is amorphous and light to dark brown.

In some instances, especially those where the humus layer is lacking and in fragments lying on the surface, the material seems weathered and grayish on the surface, and the cement is darker, and duller brown internally.

CHEMICAL AND MINERALOGICAL NATURE

Analyses show varied percentages of phosphorous in different samples, from 2.7 to 14, averaging about 9.5 and percentages of calcium from 31.3 to 26.2, averaging slightly lower than those in the associated calcareous sediments. That part of this Ca in some samples is in the form of $CaCO_3$ is suggested by strong effervescence with acid and demonstrated by X-ray patterns for both calcite and aragonite. That some is phosphate (all in certain samples) is shown by X-ray patterns corresponding to apatite. The peaks in these patterns were not sharp enough to indicate with certainty which of the several varieties of apatite were represented. (X-ray analysis by John C. Hathaway, U. S. Geological Survey).

The differences between various samples are doubtless due to different degrees of replacement of the $CaCO_3$ by the phosphate. These may reflect differences in age, acidity, or guano supply.

The characteristic brown color of the cement probably has nothing to do with the phosphate itself. It is very similar to the color of the overlying humus and in all probability comes from organic impurities carried down during the leaching process, here assumed to be the cause of the phosphatization.

ANALYSES FOR PHOSPHOROUS AND CALCIUM*

Sample number	Atoll	% phosphorous (as P) (Rapid chemical)	% phosphorous (as P) (Spectrographic)	% calcium (as Ca) (rapid chemical)
Phosphate rock layer:				
2	Jemo	7.7	9.0	33.4
5	Jemo	13.2	14.0	31.3
6	Jemo	6.0	4.3	36.2
8	Kwajalein	4.0	3.7	35.8
9	Kwajalein	12.0	10.0	32.8
10	Kwajalein	13.4	12.0	31.8
13	Bikar	4.4	4.6	34.5
20	Bikar	5.2	5.0	34.8
16	Bikar	3.0	2.7	34.4
17	Bikar	5.0	7.9	34.0
Unconsolidated layer immediately beneath phosphate layer:				
3	Jemo	1.4	1.7	34.5
14	Bikar	0.54	0.5	36.2
18	Bikar	0.56	0.5	35.0

* Analyses by rapid chemical method by Harry F. Phillips, Katrine E. White, Leonard Shapiro, and Frank Borris (for method used see Shapiro and Brannock, 1952), and spectrographic analyses by Harry J. Rose, all of the U. S. Geological Survey.

ECOLOGY AND HISTORY

A detailed ecological consideration of this rock is being prepared for presentation elsewhere, but it may be appropriate to summarize the conclusions here.

It is considered that the phosphate rock is of recent or even, in some places, contemporary origin. Its occurrence is usually in association with a layer of acid (pH 4-6) raw humus, which is generally freely spattered with guano from sea birds and is itself also high in phosphorous. This suggests the conclusion that the coincidence of bird guano and acid conditions leads to the cementation of the upper parts of the lime sand layers immediately beneath.

The guano is largely made up of finely divided calcium phosphate originating in the bones of fish eaten by the birds. This, under normal conditions, is washed, probably in solid form, by rainwater down through the highly porous substratum into the ground-water body, and is then commonly flushed out by tidal action. Where the guano is deposited on and washed through a layer of acid humus it is dissolved and percolates down in solution into the calcareous material beneath. Here the solution immediately becomes alkaline, precipitating out the calcium phosphate, which acts as a cement to produce the rock under consideration. It is probable that the characteristic brown color of this cement is due to impurities derived from the humus, which is of more or less the same color. By the continual bathing of the cemented particles by the acid solution from above, the carbonates may be slowly leached out, causing the softening observed in the limey particles. They may gradually be replaced by calcium phosphate, as is suggested by the brown color of the outer parts of the particles in some places. This replacement is substantiated by the X-ray analyses of certain of these samples showing absence of $CaCO_3$ as well as the discovery on Kapingamarangi and Gaferut (McKee, 1956; Niering, 1956) of similar rock, containing clastic fragments but proving to be 100 percent phosporite or apatite.

This process seems to take place only under a very definite set of circumstances, i.e. where there is guano deposition on the surface of raw humus accumulation. The occurrence of raw humus accumulation in lowland tropics is most unusual, almost unique. In the islands under discussion it happens only under one species of tree, *Pisonia grandis*. Although looked for, no such humus was found under any of the dozen or more other common trees in the area. Why *Pisonia*, alone, produces such humus is not known.

Pisonia grandis often forms exclusive groves and forests that seem to be favorite nesting and roosting places for several sorts of fish-eating sea-birds, which provide the guano. In the recent past such groves were much more common than now (Agassiz, 1903) but in many places have been cut to give place to coconut plantations (Niering, 1956).

Repeated searches in places where large numbers of these birds roost and nest in other kinds of trees, and of great rookeries where other fish-eating birds nest on bare ground of similar calcareous sediments to those under the *Pisonia* trees revealed no instances of cementation. This is probably because of lack of a source of acid to dissolve the calcium phosphate in the guano.

Many field tests of the guano itself, after it had dried, showed a reaction of pH 6.5 (in one instance pH 7). Within this range the phosphate is scarcely soluble. There also seems to be little or no alteration of coral pebbles which are encrusted with guano, even though they are naturally very porous. Qualitative tests for phosphate in the subsurface layers of a pebble so encrusted gave negative results.

The suggestion has been made (Shaw, 1952; P. E. Cloud and Z. S. Altschuler, personal communications, 1953, 1955) that the sequence may be the reverse of that outlined here, that the presence of previously developed concentrations of bird guano or of phosphate rock may favor the growth of *Pisonia*, and be responsible for the existence of the *Pisonia* forests. This may be possible, though the widespread occurrence of *Pisonia*, both as a component of mixed forests and as pure stands, in places where there is no obvious guano or phosphate rock suggests that this is not so. However this may be, one sequence of beds found in 1952 on Bikar Islet, Bikar Atoll, indicates that the process described above does take place in essentially the order suggested. Pits dug in several parts of Bikar Islet show that the well-developed phosphate beds which cover much of this islet are covered in their western three fourths by relatively recent storm-deposited sand, tapering off eastward and not reaching the eastern side. Where these beds are not buried by sand they are covered by a layer of humus up to 20 cm thick. The beds themselves are from 20 to 60 cm thick. Where they are covered by sand the raw humus has disappeared, though the lower layers of sand are darkened. On the surface of this sand, under a dense *Pisonia* forest, is a miniature of the sequence described. The surface is covered by about 5 cm of brown raw humus spattered with guano. This is underlain by a thin very fresh-looking cemented layer with the cemented particles exactly similar in texture to the sand immediately beneath and above the older consolidated phosphatic layer that extends over much of the island. This is interpreted as resulting from present-day operation of the process by which the phosphate is thought to be formed. It certainly could not be accounted for by the theory that the phosphate preceded the *Pisonia* forest.

Another occurrence that indicates that the phosphate was deposited subsequently to the growth of the *Pisonia* trees was described by Hatheway (1953, p. 58) as follows:

> A fragment of rock removed during the excavation of the soil pit was suggestive of the length of time necessary for formation of the hardpan. One side contained a semi-cylindrical cavity approximately 2 inches in diameter. The rock was hardest and darkest around the cavity, which apparently had once been occupied by the root of a tree. It is suggested that the rock must have formed around the root after the latter had attained a diameter of 2 inches, for had the root penetrated the rock after the latter had formed, it surely would have shattered the brittle rock during its increase in diameter. Further, the rock must have formed around the root while the latter was still alive or only recently dead. Coarse, unconsolidated sand would quickly have filled in the cavity left by the decaying root had the latter rotted before the rock was formed. This suggests that the phosphate rock formed very rapidly, perhaps within less than 100 years, although the length of life of the root of an unknown species of tree under the conditions described is of course not known.

This piece of rock is still in the possession of Dr. Hatheway. These occurrences, together with the existence of a humus layer under *Pisonia* with no

phosphatic hardpan where birds are absent, suggest that this alternative theory is untenable. The occasional existence of a hardpan layer without *Pisonia* and without humus does not constitute an obstacle to the theory here accepted, as, in the case of such an occurrence in Kapingamarangi, the *Pisonia* forest is known to have been cleared off within historic time. The same history is at least possible in Onotoa, Gilbert Islands. In Gaferut, another such case, there is evidence of a destructive typhoon in the presence of large blocks of reef-rock thrown up on the reef flat. This storm may well have swept off the *Pisonia* trees as well as the humus, leaving the bare phosphatic rock. Not enough is known about the occurrences of this kind in the western Indian Ocean, but with the long history of human activity there, it is not improbable that the forests were destroyed by human agency leaving the phosphate, much of which was subsequently mined.

The alternative hypothesis held by some (e.g. Altschuler, written communication, 1956) that the normal mode of formation of such phosphate rock as is described here is by direct reaction between guano and limestone seems untenable. It is suggested that the fresh guano contains "acid solutions of relatively soluble phosphate" and that these react with limestone to form apatite. Failure to find phosphate rock under guano deposits without *Pisonia* humus or under trees other than *Pisonia*, the almost neutral reaction of fresh guano, and the powerful ammonia odor obvious around bird rookeries are all indications contrary to this idea. Contrariwise, the frequent coincidence of *Pisonia*, birds, and phosphate rock suggests that the theory advanced in this paper may more probably describe the "normal mode of phosphatization," on these atolls.

It is considered that the process suggested here and especially the evidence that it is a contemporary one, makes unncessary and unlikely Hutchinson's conclusions (G. E. Hutchinson, 1950, p. 195, 374-376) that the major climatic belts in the Pacific have shifted since the Pleistocene. They may, of course, have shifted but his conclusions were largely based on his assumption that guano in large quantities could not be produced on a wooded island but only on a bare open one where such birds as sooty terns nest in great rookeries. Observations actually show, not only that sufficient quantities of guano are produced by tree nesting and roosting birds, but that the *Pisonia* forests provide a means of fixing and holding the phosphate which otherwise, except on the very driest islands, would be washed away. Examination of sooty tern rookeries, showed that these birds apparently deposit little or no guano on land; at least there seems to be no evident accumulation in their rookeries, even on dry atolls such as Pokak and Bikar. The partial phosphatization of the Christmas Island sands (G. E. Hutchinson, 1950, p. 182-183), which fits into Hutchinson's ingenious explanation, may be equally well explained by the poor development of *Pisonia* on that island. In 1936 there was only one scraggly half-dead little grove of *Pisonia* on the entire atoll. If it should turn out that the phosphatic material on these dry equatorial islands is similar to that described here it would suggest that these areas had formerly been wet enough to support *Pisonia* forest rather than that the present wooded atolls had once been dry enough to be open.

RELATION TO OTHER ISLAND PHOSPHATE AND GUANO DEPOSITS

The question immediately arises of whether all island phosphate deposits are of the origin proposed here. Because of extremely diverse modes of occurrence this seems very unlikely. Certainly where there are enormous concentrations of some kinds of birds, such as on the Peruvian guano islands, large accumulations of guano not altered to phosphate rock occur. This may also happen on such extremely dry islands as Jarvis, Howland, and Baker, though from the inadequate available descriptions, this is not evident. For the present, because of lack of exact enough information, the dryer Pacific Equatorial Islands can be excluded from the discussion. Existing data on them are summarized by G. E. Hutchinson (1950). Accumulation of guano may also occur on islands where the substratum is solid rock as on Motu Manu near Oahu and Los Coronados, off Baja California. What the effect of this guano is on the underlying material is not certain, though the alteration of the Clipperton Island trachyte to phosphate (Teall, 1898; Lacroix, 1939) may indicate that there is an effect.

The massive, deep, unbedded deposits on such islands as Angaur, Kita Daito Jima, Nauru, Ocean, and Makatea can scarcely be the result of a process comparable to that described here, as those deposits are not in the form of horizontal beds of phosphatic sandstone but are more in the form of a fine-grained silty deposit between limestone pinnacles or irregularities on a buried karst-like surface. It is more likely that they may result from situations comparable to that on Washington Island, where a fresh-water lake bottom is composed of phosphatic mud (Elschner, 1915, 1923; G. E. Hutchinson, 1950, p. 184-185). It is not considered probable that these massive occurrences result from the complicated process suggested by Ranson (Proc. 8th Pacific Science Congress, ined.).

ECONOMIC SIGNIFICANCE

During the last half of the 19th century and early part of the 20th there was active exploitation of the "guano" of atolls in various parts of the Pacific. The most productive were apparently the drier atolls in the equatorial belt and the nature and origin of the material mined there is not altogether clear. It may have been accumulated under different circumstances from those described above, as there are now no *Pisonia* groves on the islands concerned. However, some of what was generally termed "guano" was definitely comparable to the rock here described. This was true at least on Fanning and Gaferut atolls. The Japanese conducted an extensive survey of material of this sort in their Micronesian islands (Aso, 1940), estimating that on Bikar Islet alone there existed about 12,000 cubic meters. On Ebon, active exploitation was taking place under their auspices right up to 1941. Hatheway (1952) found in 1952 a large heap of mined phosphate rock piled there, ready for shipment, which was said by the natives to have been dug by the Japanese before the war. However, on the scale of modern phosphate operations even the largest such deposits known are probably of trifling economic significance.

Ecological consideration is pertinent here, also. There are indications of phosphate deficiency in the soils of some atolls that have been subject to

heavy copra harvest. Because of a relatively high phosphate content of this crop, exhaustion of the phosphorus in soils of the plantation is, sooner or later, inevitable unless it is replenished. It is also clear that the native owners of these plantations are not likely to be financially able to import commercial fertilizers. It would seem probable that these little deposits would be quite adequate for the use of the natives, to fertilize their coconut plantations. The mode of occurrence as surface beds of soft, friable rock makes it entirely feasible for them to dig it up in small quantities and transport it to where it would be needed. That it would be effective for their purpose is shown by the luxuriance of the coconut trees on the part of Jemo Island where plantations are on soil containing a rather broken-up occurrence of this rock compared with their unhealthy condition on nearby coral sand unmixed with phosphate rock. It is of interest that essentially the same conclusions were reached by Hutchinson with regard to the deposits on the islands north of New Guinea (R. C. Hutchinson, 1941, p. 242).

Exploitation in such small quantities for local use would stretch the available supply over a long period. There is even some indication that this can be regarded as a renewable resource if some *Pisonia* forests are not destroyed and the birds are not driven away from them or killed. The ancient Marshallese custom of regarding certain islets, e.g. Jemo and Bikar, as bird refuges is probably responsible for there still being in existence situations where this interesting phenomenon could be studied.

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THE STATUS AND NOMENCLATURE OF STRATIFIED EVAPORITES

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ABSTRACT. Current descriptive terminology implies that evaporites interbedded with normal sedimentary limestones and marls are metamorphic. As the criteria distinguishing metamorphosed evaporite beds from those that have been diagenetically recrystallized are obscure, a new non-commital terminology is erected. This can also be applied to evaporitic textures in salt domes.

THE STATUS AND NOMENCLATURE OF STRATIFIED EVAPORITES

As more fundamental data on stratified evaporites accumulate in current literature, it becomes demonstrably more apparent that their status as sediments is declining. Whereas they could once be grouped in their entirety as rocks formed by sedimentary processes, there is little doubt that some, if not the majority, could now be quite logically grouped as resulting from metamorphism. The trend is clear in the recent study of gypsum-anhydrite deposits in Indiana (Bundy, 1956).

Metamorphism has been defined (Turner and Verhoogen, 1951, p. 368) as "the mineralogical and structural adjustment of solid rocks to physical or chemical conditions which have been imposed at depths below the surface zones of weathering and cementation and which differ from the conditions under which the rocks in question originated". If this definition is rigidly adhered to, the Indiana rocks are undoubtedly metamorphic. They have passed through at least one stage of adjustment at an unknown depth, during which the gypsum was converted into anhydrite, and have developed textures, such as gneissoid (Bundy, 1956, p. 242), normally associated with metamorphic rocks. By strict analogy it is probable that many shales, which commonly alter structurally and mineralogically during compaction, could be called metamorphic rocks, yet most sedimentary petrologists would hesitate to take so drastic a step.

The problem, which is a real one, in fact resolves itself into the distinction, if any, to be drawn between diagenesis and metamorphism. Moreover "metamorphic" evaporites are often associated or even interbedded with virtually unaltered limestones. Not that one would expect an equivalent degree of alteration limestones, as obviously the effects of metamorphism depend on the original nature of the transformed rock. In the early stage of subjection to high pressures and possibly increased temperatures, bedded evaporites might be expected to change more rapidly than limestones. Nevertheless, the mere fact that "primary" limestones may interdigitate with "secondary" evaporites suggests that metamorphic may perhaps be too strong a term to use when describing the processes affecting many evaporite sequences.

The drawing of such a fine distinction between metamorphism and diagenesis, especially in the presence of textures and structures so clearly secondary, is purely arbitrary and probably depends more on the nature of the associated non-evaporitic beds than on the evaporites themselves. In actuality many evaporitic successions are interbedded with limestones or marls showing

little post-depositional change apart from dolomitization, a diagenetic rather than a metamorphic effect to most sedimentary petrologists.

A criterion depending on external factors however, is clearly open to criticism, for where those factors may be absent or unobservable, there appears to be no reliable method of deciding whether an evaporite bed has simply recrystallized diagenetically or has altered as a result of metamorphism through the action of pressure and heat. Thus, perhaps petrologists would do well to avoid any terminology that indicates a metamorphic genesis for evaporites where the evidence is dubious or where diagenesis is more probable. Although normally used in a purely descriptive sense, terms such as "gneissic porphyroblastic anhydrite" can only be misleading. In view of the commonly accepted sense of metamorphism, it is doubtful that evaporite beds showing secondary structures and textures should *ipso facto* pass into a province of petrology away from that of sedimentology. Phemister (1956) pointed out that to use such descriptive terms as diablastic, granoblastic, etc., for diagenetically recrystallized limestones in Scotland and thus imply that the rocks are metamorphic, is deceptive and therefore undesirable. Sander (1936), also in reference to limestones, said that all terms of petrographically ambiguous nature, such as primary schistosity, should be avoided.

To describe the texture, whether it be primary or secondary, is it not thus becoming essential to devise suitable descriptive and unambiguous names? In the belief that it is, the following tentative descriptive scheme is put forward:

Primary Texture (Depositional)	*evapocrysts*—individual primary evaporite grains
	evapocrystic—texture in which no linearity or lamination of primary grains is present
	evapolensic—a non-porphyritic, roughly laminated texture
	evapo-porphyrocrystic—a texture in which large primary grains are set in a finer grained matrix
Secondary Texture (Recrystallization)	*neocrysts*—individual secondary evaporite grains
	neocrystic—a non-laminated texture
	neolensic—a non-porphyritic, roughly laminated texture
	neo-porphrocrystic—a texture in which large secondary grains are set in a finer grained matrix

On this scheme, a "gneissic porphyroblastic anhydrite" would be a coarsely laminated *neo-porphyrocrystic* anhydrite, a more prolonged but nevertheless unambiguous description of the rock in question.

The application of this new terminology to unstratified evaporites is debatable. In salt domes and some associated cap rocks "flowage" (Goldman, 1952, p. 18) occurs and the rocks could quite justly be called metamorphic

(and described in metamorphic terms) with a greater degree of certainty than in the case of their bedded equivalents. It is believed however, that some useful purpose would be served by maintaining a consistent treatment and using the new terms, especially those applicable to recrystallization, in describing the textures present within domes. A rather pertinent factor is that within domes, which may or may not be diapiric, primary sedimentary salt fragments or clasts (Goldman, 1952, p. 6) are sometimes present in unaltered state apart from physical distortion. Likewise, relatively unchanged marls, sandstones and shales may be present and fossil algal structures are not uncommon (Rogers, 1918; Barton, 1926; DeGolyer, 1925) all indicating alternation in the associated evaporites for which the term quasi-metamorphic may be more appropriate metamorphic. The presence in some domes of algal filaments tends to confirm this and throws a little doubt on the use of terms having a metamorphic connotation.

Although the system proposed is slightly cumbersome, it is hoped by it to deter workers in the evaporite field from using terms capable of being genetically misunderstood. Likewise it is hoped that evaporites, in particular the bedded varieties, may remain, at least for the most part, in the province of sedimentology. The terms outlined above are capable of extension to cover other primary and secondary textures and thus may prove acceptable to those engaged in the teaching of petrology to all levels.

ACKNOWLEDGMENTS

The author is grateful to numerous colleagues, including Professor F. H. Stewart, Professor J. H. Taylor and Dr. E. H. T. Whitten, for stimulating advice and discussion on this controversial subject. It is as a direct result of the contradictory viewpoints put forward during those discussions that the paper has been written, with the hope that it will focus the attention of other workers on an interesting aspect of evaporite petrology.

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ESSAY REVIEW

Die Kupferchlorid Kristallisation; by A. and O. SELAWRY (M.D.'s); P. xl, 232; 131 figs., 11 plates, 32 tables. Stuttgart, 1957 (Gustav Fischer Verlag; in the U. S. A. available from Stecher-Hafner, New York, at $10.75). —It is somewhat of a surprise to find that a very significant contribution to crystallography, mineralogy and even petrogenesis has come from the field of medicine.

The development of crystal growth and crystal morphology in response to *external factors* has been described by A. and O. Selawry, a brother and sister medical team, in a most thorough and instructive way in their treatise on the "Crystallization of Copper Chloride".

Many substances, when present in a supersaturated solution of another substance may greatly influence the crystal growth of the latter, without entering in any chemical combination with it. This influence may be much more profound than the action of "mineralizers" as commonly understood in petrology. For instance NaCl, as every undergraduate is supposed to know, has a preferred cubic habit. In the presence of urea, however, it crystallizes mostly as octahedrons, with mere traces of the cubic faces. Apparently there are strong affinities, both structural and energetic, between the (111) faces of NaCl and urea. As a result a fleeting coating of liquid (?), but structurally organized, urea covers the octahedral faces of NaCl isolating them from the mother solution and inhibiting their growth. Since they do not grow quickly, they become larger (laterally) and show excellent development against the stunted cubic faces which grew faster.

From this simple beginning—one of the very few cases susceptible at present of a crystallographic explanation—has grown an elaborate, though purely pragmatic study of the interaction between different salts and other substances, particularly proteins. Judging by the effects not only upon crystallographic form, but even more on the morphology of the crystalline aggregate as a whole, other factors, perhaps similar to reaction-series processes and resulting fluid circulation, are also at work.

The most "sensitive" of these salts is copper chloride ($CuCl_2.2H_2O$), known in the natural state as antofogasite, a fumarole mineral.

The Selawry book describes copper chloride crystallization in the presence of various inorganic and organic substances, with emphasis on proteins, specifically blood from well and sick persons. Apparently the morphological differences produced are not only reproducible, but promising enough to give serious attention to this method as a potential diagnostic tool and induce further basic research along the same line.

Geologists, mineralogists and crystallographers will be interested in the Selawry approach, which is fascinating from the points of view both of laboratory technique and of morphologic (or rather morphogenic) interpretation.

The book consists of eight parts, plus a 26-page introduction by Professor Neuhaus of Bonn. In this introduction Professor Neuhaus, in a much better way than usually found, discusses the fundamentals of crystal chemistry (*not* crystal physics) as applied to crystal growth in general and the growth of copper chloride in the presence of proteins in particular. This introduction begins with a quotation from Niggli, deploring the lack of contemporary in-

terest in morphological studies. The same feeling is also shared by this reviewer, since the study of real entities cannot be purely symbolic and must rely to a large extent on the proper understanding of morphology.

The first four parts of the book proper (written by O. Selawry) cover laboratory techniques, methodology of descriptive patterns—a real treat—and the interaction of copper chloride with various substances that are not blood proteins. At this point the field geologist who likes to map his formations on the basis of vegetation will be interested to learn that peas grown on a sandy soil produce an entirely different pattern of copper chloride crystallization than peas grown on loamy soil! (Figs. 42a and 42b). The fifth and sixth parts (jointly by A. and O. Selawry) describe more sophisticated experiments with blood compounds. The last two parts written by A. Selawry show the extraordinary powers of differentiation of copper chloride crystals in the presence of blood from various illnesses.

The extreme sensitivity of copper chloride crystallization to impurities (or "Lösungsgenossen", i.e. "solution companions") and to such factors as temperature, humidity, vibration, etc. naturally requires the most rigorous laboratory techniques to avoid disturbing influences. These techniques are described from A to Z.

Having negotiated this hurdle, the investigator comes to the crux of the matter: how to describe and correlate the variations in morphology. In this reviewer's opinion, morphology, i.e. shape (unrestricted) is not very well suited to meaningful measurements on an interval scale, and thus appears, for the present at least, to be somewhat refractory to treatment by conventional, parametric statistics. Thus no fault can be found with the Selawry approach, which is the classical naturalistic one, particularly since the authors use it with brilliant success.

They begin with the whole, namely the crystallization dish or "plate" (it is specially constructed). The circular "crystallization plate" is a completely closed system, with its own "topography". The only constant is the portion of the plate next to the rim. The other points and lines of reference depend upon the center of gravity ("Schwerpunkt"), i.e. the place where crystallization begins and from which the branching acicular crystals radiate. Since this point is invariably off center, the plate is oriented upwards from the "Schwerpunkt" and a system of mutually perpendicular bisectrices divides the plates into 12 subfields. Peculiarly enough, this relativistic system works and produces no equivocations.

Within the plate's "topography" (which localizes any portion of the growth), the morphology of the copper chloride's crystallization is treated under several headings.

(1) General picture of the entire growth on the plate
   a—Centering, ("Zentrierung"): is there one center of gravity only, or several closely spaced ones, an analogue to symmetry.
   b—Coordination, a totally different concept which expresses the perfection of the interrelationships between crystals and crystal aggregates.

c—Perfection of direction of radiating, acicular crystals ("Durch = strahlung").

d—Thickness and color (pale blue to green).

(2) Forms of development of crystal complexes, i.e. structural morphology on a relatively "large" scale (Gestalten). The basic forms, with numerous subspecies in each case are:

a—Radial forms, divided into stars, crosses and rosettes.

b—Vacuoles, i.e. empty portions of the plate "framed" by more robust crystals.

c—Transitional shapes, mostly partly open vacuoles, frequently U-shaped.

(3) Morphology of the single acicular copper chloride crystal, the basic "building block", described in terms of length, width, and "profile", i.e. crystallographic expression.

(4) Texture, i.e. smaller scale relations of the crystals within the larger structural forms. These are, again with many subtypes:

a—Straight pattern.

b—Crossed pattern.

c—Dendritic pattern.

d—Diagonal ("Quer") pattern, a particularly interesting one, from the pathologic point of view.

e—Minor types, such as finely branching, etc.

A mere enumeration of the classification of forms would be exceedingly dry; in order to appreciate the classification, one should see at first hand the magnificent photographs in the book. In general, it may be said that the Selawry's have attacked the problem of the crystallization of copper chloride on *four levels or orders of magnitude*: the single crystal; the simple aggregate (texture); the aggregate of aggregates (structure or "Gestalt"); and the general development of the entire "body" i.e. the entire complex within the plate. The analogy to petrology is complete: petrologists deal with the mineral grain, the texture of the rock, its large scale structure, and finally the configuration and shape of the entire lithologic unit, be it a batholith or a sand lens.

It is remarkable that in copper chloride crystals—again just as in rocks—there is a notable correspondence between these four morphological factors: a certain texture is related to a certain structure or "Gestalt", and frequently to a certain general aspect of plate "topography". This indeed reminds us that aphanitic rocks occur seldom—to put it mildly—in a batholith, and that highly micaceous sediments (i.e. high in platy particles) are generally relatively fine grained.

It is refreshing to see what a properly conducted morphologic-morphogenic study can accomplish. The Earth Sciences also need more studies of this type, studies where the data is directly visible and thus is not divorced from reality.

How reliable are the results? The Selawry work is based on 22,000 experiments, each one of them replicated *five* times or more (up to 20 times)—over 100,000 observations all told. Their conclusion is that if four replicas out of five (each experiment is replicated on five separate crystallization plates)

are identical, then the result is to be trusted. This 80 percent probability (or significance) is about as much as this reviewer ever hopes to attain in solving geologic problems loaded with numerous variables.

The Selawry research was undertaken 16 years before publication on their own "private initiative". Only during the last four years did it obtain financial support from German foundations. A good example to remember: research should begin with an idea, not with a budget.

One more added attraction: the book is not only extremely well organized, but is very clearly written. The sentences are simple and not at all like the formidable "scientific German" that has been famous for generations.

The Selawry book is recommended as a very useful reference work for every University—or even every Earth Science Department—Library.

PAUL D. KRYNINE

Crystal Structures, Section IV; by RALPH W. G. WYCKOFF. P. 150. New York, 1957 (Interscience Publishers, Inc., $7.00).—This section contains chapters XI, "Miscellaneous Inorganic Compounds," and XII, "Silicates." Its appearance now completes a fine three-volume work containing reviews of practically all structures published so far. The issuance of supplementary sheets for inclusion in the looseleaf volumes is novel, and so far has been eminently successful, as a means of keeping the book up to date. The first volume, issued in 1948 and supplemented in 1951, contains chapters 1 through 7, covering the generally simpler inorganic crystalline compounds, from elements to and including three-element compounds of formula-type $R_n(MX_3)_p$; the second volume (1951, 1957) covers the remaining three-element compounds, the hydrates and ammoniates, miscellaneous inorganic crystals, and silicates; the third volume covers organic crystals in four chapters.

Many drawings and diagrams are still to be issued for each of the chapters, and none are included in section IV, presently reviewed. Cross references in a few cases make drawings of silicates unnecessary, but a few diagrams showing the principles of combination of SiO_4 groups would have been very useful.

The reviewer would prefer to see silicates described under the now-widely-used terms of Greek origin that were (first?) used by Strunz (1941), namely nesosilicates and sorosilicates instead of "discrete silicate groups," inosilicates instead of "silicate chain structures," phyllosilicates instead of "silicate sheet structures," and tectosilicates instead of "network silicates." The last term is too similar to the crystallographic term "net," meaning a two-dimensional lattice.

Advantages of periodic revisions and additions far outweigh the minor inconveniences of the sectional pagination. It takes only a few minutes to learn how to find compounds without an alphabetical index. This book, with periodically updated contents, is essential wherever the much more elaborate annual volumes of *Strukturbericht* and *Structure Reports* are either not available or too detailed.

HORACE WINCHELL

Lehrbuch der Mineralogie, 2d ed.; by WALTER SCHMIDT and ERNST BAIER. P. 376; 302 figs. Basel, 1955 (Birkhäuser Verlag, Swiss fr. 30.80, paper cover; 35.-, cloth bound).—This second edition of a comprehensive textbook, prepared by Prof. Baier after the death of Prof. Schmidt, follows the same general outline as the first edition (1935). *General Mineralogy* (p. 17-198) includes a somewhat difficult section on crystallography; its other sections are well organized throughout, covering crystal optics, deformation, crystal structures and internal binding forces, phase diagrams, kinetics and dynamics at crystal surfaces, and partly-crystalline states. *Special Mineralogy* (p. 199-356) includes a few pages of geochemistry and mineral paragenesis, and a systematic description of minerals subdivided conventionally as elements, sulfides, oxides, etc., oxygen salts including silicates, and halogenides. A bibliography of about 65 of the most useful books (emphasizing German ones, but by no means excluding foreign literature) and 15 periodicals of interest to the serious student of mineralogy, an index of mineral and rock names (more than 700 mineral names, over 850 entries), an index to references on ores, a geochemical index, and an outstanding general index (1500 entries) make this one of the best indexed texts available.

Prof. Baier's emphasis on mineralogical principles rather than localities and purely descriptive matters in the descriptive section is highly successful; the de-emphasis of simple criteria for actual identification of minerals has been carried rather far, but is quite proper if this book is to be used in connection with suitable determinative tables. The first edition of this book was a considerable departure from the old school of mineralogical teaching: the second edition has retained the advantages, and largely remedied the shortcomings of the first, and deserves to be carefully studied by writers of texts in other languages. Its very existence as a second edition testifies to its success with German-speaking students and professors alike.

HORACE WINCHELL

Irradiation Colours and Luminescence; by K. PRZIBRAM. P. xiv, 322; 73 figs. London and New York, 1957 (Pergamon Press, $10.00).—This book is essentially descriptive: it serves a good purpose in bringing together many data (with references) in a convenient package. The phenomena of irradiation colors, or colors produced by natural and artificial irradiation by x-rays, gamma rays, alpha rays, beta rays, heat, light, etc., are thoroughly summarized and, in most instances, adequately documented. The contents of the book may be outlined in terms of the following abbreviated chapter headings: Introduction; Apparatus; Experimental coloration of alkali halides; Photoelectric effects; Theoretical treatment (only 20 pages); Coloration of glasses; Coloration by colloids; Theory of growth of color intensity; Luminescence; Luminescent excitation agents; Natural coloration; Rocksalt; Other halides; Fluorite; Oxides and sulfides; Carbonates; Sulfates; Nitrates and phosphates; Silicates; Diamond; Pleochroic haloes; Conclusion.

A more adequate treatment of modern physical theory would improve the general balance of the contents. The bibliography (49 pages), table of contents (6 pages), author index (11 two-column pages), and subject index (dis-

appointingly brief entries, only 4 two-column pages) take up 70 pages in all.

The translator's preface shows that the author's original book, *Verfaerbung und Lumineszenz* (Vienna, 1953), has been brought up to date as of about 1954, chiefly by the inclusion of some 500 additional references by which the reader may look up the more recent developments for himself.

HORACE WINCHELL

Robert Hooke; by MARGARET 'ESPINASSE. P. vii, 192; 16 pls. Berkeley, 1956 (University of California Press, $3.75).—Robert Hooke was, in many ways, the last of the "universal men" of the Renaissance. An extraordinarily skillful experimenter, an inventor, an architect of no mean ability, a "mechanik" of great dexterity, and a physicist whose mind literally teemed with ideas and intuitions on the nature of the world, he has, somehow, never received the attention which his genius deserves. Overshadowed by the overwhelming power of Sir Isaac Newton and the penetrating common sense of Robert Boyle, Hooke has come down through the centuries as a somewhat cantankerous and odd fellow, known in science only by Hooke's law and his detailed drawings of magnifications of such constant but uncomfortable partners of man as the louse and the flea.

Miss Margaret 'Espinasse, Lecturer in English at the University of Hull, Yorkshire, England, has attempted in this slim volume to correct the inaccuracies of the traditional view of Hooke and set the record straight. There is no doubt that a revision of Hooke's role in the development of modern science is long overdue, but Miss 'Espinasse's work is clearly inadequate.

The basic fault of this book is that, as the author freely admits in the preface, she has little or no scientific training. This, plus a lack of knowledge of the history of science which is somewhat less pardonable, so completely distorts her perspective that her "revision" bears little relationship to historical reality. There are so many simple errors of fact and interpretation that space does not allow them all to be catalogued here. Two examples will suffice to illustrate Miss 'Espinasse's method.

There are two poor ways of increasing the reputation of one's chosen subject: by denigrating the accomplishments of his rivals, and by attributing greater things to him than he actually accomplished. Miss 'Espinasse uses both. In spite of her remarks on Newton's genius, she clearly implies that he was somewhat over-rated. More than this, she charges him (chapter II) with a pernicious effect on science in the eighteenth century—a charge which requires a great deal more supporting evidence than is here provided. She points to the almost inhuman aspects of Newton's "induction" and his famous refusal to "frame hypotheses." But she does not distinguish between Newton's refusal to frame a hypothesis to account for the phenomenon of attraction and his willingness, as shown so blatantly in the *Optics*, to use hypotheses as aids to further investigation. She misses, therefore, the whole point of Newton's position and accuses him of something of which he is clearly innocent.

More annoying than this is the constant repetition of the "modernity" of Hooke's views in science. To what end have two generations of historians of science labored if their efforts are so in vain? If there is any point that histor-

ians have belabored, it is that superficial resemblance of past scientific theories to modern ones is a totally unreliable yardstick by which to measure the achievements of the past. Yet, in this volume, the reader is literally bombarded by such analogies. We are told (p. 7) that "he proved clearly that in combustion something (oxygen) is taken from the air and combines with the burning substance, and that this something is necessary to combustion." This is palpable nonsense! In her efforts to make Hooke "modern," Miss 'Espinasse even cites passages which have absolutely nothing to do with the subject at hand.

> "He also discusses, as the ground of the elasticity of bodies, a kinetic theory of matter: that each material body is in a perpetual 'Vibrative motion' which is 'peculiar and appropriate' to the particles of each, and that 'Two or more of these particles joyned immediately together and coalescing into one become of another nature and make a compounded particle differing in nature from each of the other particles."

For example, the reference to "kinetic theory"—illustrating Hooke's modernity—is supported by a quote (p. 71) which sheds little light on the problem of elasticity.

The book has a bibliography and an index. A definitive biography of Robert Hooke, however, remains to be written. L. PEARCE WILLIAMS

Eighth Pacific Sicence Congress, Proceedings. Quezon City, 1956. (National Research Council of the Philippines, University of the Philippines).—Several large and well printed volumes, including the reports of the Fourth Far-Eastern Prehistory Congress, present the results of the meetings at the University of the Philippines in November, 1953. Volume I includes formal proceedings and organizational data, and several informative public addresses. Volumes II and IIa on Geology, Geophysics, and Meteorology will especially interest earth scientists. They include reports on ten symposia dealing with problems of volcanology, paleontology and stratigraphy, mineral deposits, seismology, tectonics and submarine geology. Meteorology papers cover forecasting techniques, rainfall and cloud physics, typhoons, and climatology.

A symposium on medicinal plants (vol. IVa) and the first fascicle of the report on prehistory, archeology and physical anthropology, which includes eight papers on Chinese archeology have also been issued.

These papers are largely descriptive, but include considerable new data bearing on major problems of the Pacific area.

JOSEPH T. GREGORY

Principles of Engineering Geology and Geotechnics. Geology, Soil and Rock Mechanics, and Other Earth Sciences as Used in Civil Engineering; by DIMITRI P. KRYNINE and WILLIAM R. JUDD, P. XIII, 730; 478 figs., New York, Toronto, and London, 1957 (McGraw-Hill Book Company, $10.00).—This timely book, written jointly by an engineer and a geologist, undoubtedly will serve both engineers and geologists well. It is so designed and executed as to provide practicing engineers with sufficient information on geology and

other earth sciences for the planning, design, and construction of engineering works and to afford geologists a basic understanding of the engineering requirements and procedures involved in such activities. Yet the book makes no pretense of transforming engineers into geologists, nor geologists into engineers.

In the past two or three decades, the field of engineering geology has been broadened in its scope and extended in its application. Up to about 1930, engineering geology consisted mainly of the application of geology to dam site problems by college professors employed as consultants. Subsequently, it has been constantly broadened to include all other earth sciences, insofar as they are applicable to the solution of engineering problems. At the same time, it has been extended to all other types of engineering construction works, such as tunnels, bridges, highways, embankments, canals, and river rectification projects and to various other matters such as landslides, subsidence, sedimentation, and shoreline problems. The application of engineering geology is now carried on to a large extent by technicians who have a working knowledge of several branches of geology, soil and rock mechanics, geophysics, and hydrology as well as an understanding of engineering requirements and construction procedures. The term *geotechnics*, which is carried in the title of the book, is applied to the use made of all the earth sciences in engineering problems. It is defined, in effect, as "a new branch of human knowledge" evolving from "engineering geology reinforced with useful information from other earth sciences and adequate notions of engineering." It is neither stated nor implied that any one geotechnician should be proficient in all branches of geotechnology.

The book contains 19 chapters, each followed by a lengthy list of references. It covers comprehensively the entire field of engineering geology and geotechnics, differing from other books on engineering geology in both its approach and scope. Case histories, as such, are avoided, but numerous and varied engineering projects are referred to for the purpose of illustrating principles. The first eight chapters are devoted to basic data and principles. With the exception of chapters 4, 6, and 8, on soil mechanics, subsurface exploration, and rock as a construction material, respectively, these chapters contain little that geology students do not learn in undergraduate courses in geology. For engineering students who take only one course in geology, all the material presented in the first eight chapters is essential. All these chapters are sufficiently inclusive to afford the student or reader an adequate background for dealing with actual problems.

The material presented in chapters 9 through 18 bears much more directly on engineering and construction problems. Some of these chapters, especially 10, 11, 12, and 17, on frost and permafrost, shoreline engineering and river improvement, elements of sedimentation engineering, and landslides and other crustal displacements, respectively, contain much elementary geology, and might well have preceded the other chapters. The subjects covered in the remaining chapters of this section include tunnels, site exploration and foundations for buildings; bridges and pavements; earthwork; earthquakes and aseismic design; and masonry dams.

On the whole, the individual chapters are well written and adequately cover their respective fields. The final portion of chapter 15 (masonry dams), especially pages 580 to 589, is an exception in that it tends to oversimplify the geological investigations for a masonry dam. The subsurface exploration program suggested on these pages is possibly sufficient for small projects in regions of generally good rock, but for large projects in regions of deformed and deeply weathered rock and especially in limestone terrains, much more exploration is required. In some instances, hundreds of deep core borings must be made in order to determine whether a given site is even usable. Subsequently, other hundreds of exploratory borings may be required to determine the position, extent and character of the defects which must be taken into account in the design of the structures and in the planning of the foundation preparation and remedial treatment programs. At some large masonry dam projects built on deformed and cavernous limestones, nearly a hundred thousand linear feet of borings were made in the pre-construction stages. At such sites, the geologist can accomplish nothing of value by making "a few tentative explorations" with "the aid of a hand auger and shovel".

The final chapter, "Some Legal Aspects of Geotechnics," presents some of the basic principles of law applicable to foundation excavation and other engineering construction projects. Most corporations and government agencies engaged in heavy construction have competent legal staffs which not only furnish sound legal advice, but handle all sorts of legal matters ranging from simple contracts to serious litigations. Small firms and consultants are not always so well informed on the legal aspects of geotechnics. Although state laws are far from uniform, the material presented in chapter 19 should prove useful to those who do not have the services of a legal staff.

The book is well written and contains a large store of information useful to both engineers and geologists. It is well illustrated with numerous line drawings and half-tones. There are few typographical errors, of which "*W*echanics" (2.8, page 54) is perhaps the most glaring. The airphoto of Fort Randall Dam under construction (page 287) lacks a figure number. In the opinion of this reviewer, whose experience includes both the teaching and the practice of engineering geology, the book is excellent both as a textbook and as a reference book. Admittedly, its success as a textbook will depend, in a very large measure, upon the adequacy of the instructor's notions of both geology and engineering.

BERLEN C. MONEYMAKER

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